



A review on the CFD analysis of urban microclimate

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ABSTRACT

Urban microclimate studies are gaining popularity due to rapid urbanization. Many studies documented that urban microclimate can affect building energy performance, human morbidity and mortality and thermal comfort. Historically, urban microclimate studies were conducted with observational methods such as field measurements. In the last decades, with the advances in computational resources, numerical simulation approaches have become increasingly popular. Nowadays, especially simulations with Computational Fluid Dynamics (CFD) is frequently used to assess urban microclimate. CFD can resolve the transfer of heat and mass and their interaction with individual obstacles such as buildings. Considering the rapid increase in CFD studies of urban microclimate, this paper provides a review of research reported in journal publications on this topic till the end of 2015. The studies are categorized based on the following characteristics: morphology of the urban area (generic versus real) and methodology (with or without validation study). In addition, the studies are categorized by specifying the considered urban settings/locations, simulation equations and models, target parameters and keywords. This review documents the increasing popularity of the research area over the years. Based on the data obtained concerning the urban location, target parameters and keywords, the historical development of the studies is discussed and future perspectives are provided. According to the results, early CFD microclimate studies were conducted for model development and later studies considered CFD approach as a predictive methodology. Later, with the established simulation setups, research efforts shifted to case studies. Recently, an increasing amount of studies focus on urban scale adaptation measures. The review hints a possible change in this trend as the results from CFD simulations can be linked up with different aspects (e.g. economy) and with different scales (e.g. buildings), and thus, CFD can play an important role in transferring urban climate knowledge into engineering and design practice.

1. Introduction

The United Nations (UN) and the World Bank anticipate a rapid increase of the percentage of the world population living in urban areas within the course of the 21st century [1,2] (Fig. 1). This change is expected to occur due to the increase in the number of cities, migration from rural to urban areas and transformation of some rural settlements into urban areas [3]. Recently, making “cities and human settlements climate resilient and sustainable” is marked as one of the sustainable development goals by the UN [4]. As a result, research on sustainable habitats and related topics is gaining importance and will continue to do so in the coming years [5].

Urban settlements are formed by replacing natural surroundings by urban environments and the latter create their own, unique microclimates.¹ In his pioneering publication “the Climate of London”, Luke Howard [6] documented that urban microclimates can be substantially different from their rural counterparts as the former tend to produce and retain more heat and are therefore characterized by higher temperatures. This phenomenon is commonly known as the Urban Heat Island (UHI) effect, a term first used by Manley in 1958 [7], although Erell et al. [8] mention it might have been coined earlier.

Interpreting the impact of the UHI effect merely as an “increase of temperature inside urban areas” would be an oversimplification. The

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¹ According to the Meteorology Glossary of American Meteorological Society (AMS) (<http://glossary.ametsoc.org/>), the term *microclimate* is defined as “the fine climatic structure of the air space that extends from the very surface of the earth to a height where the effects of the immediate character of the underlying surface no longer can be distinguished from the general local climate.” From a spatial perspective, the glossary defines the *meteorological microscale* as the “horizontal spatial scales of 2km or less.”

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Nomenclature

ACH	Air change rate (1/h)
AIAA	American Institute of Aeronautics and Astronautics
AKNKE	Abe-Kondoh-Nagano k- ϵ turbulence model
AMS	American Meteorological Society
AQI	Air quality index (dimensionless)
AT	Air temperature ($^{\circ}\text{C}$)
BEC	Building energy consumption (W)
BES	Building Energy Simulations
CFD	Computational Fluid Dynamics
CHTC	Convective Heat Transfer Coefficient ($\text{W}/\text{m}^2 \cdot \text{K}$)
CKEKE	Chen-Kim Extended k- ϵ turbulence model
CP	Pressure (coefficient) (dimensionless)
DBT	Dry-bulb temperature ($^{\circ}\text{C}$)
DKE	Durbin k- ϵ turbulence model
DNS	Direct Numerical Simulation
DSGS	Deardorff Subgrid-scale
ϵ (TDR)	Turbulence Dissipation Rate (m^2/s^3)
E (TKE)	Turbulent Kinetic Energy (m^2/s^2)
EBM	Energy Balance Models
ECN	Economy (currency)
ED	Eddy Diffusivity turbulence model
EPMV	Extended PMV (dimensionless)
Fr	Froude number (dimensionless)
FYI	First Year Index (year)
HF	Heat flux (W/m^2)
HVAC	Heating Ventilation and Cooling
IAT	Indoor air temperature ($^{\circ}\text{C}$)
k (TKE)	Turbulent Kinetic Energy (m^2/s^2)
LRNKE	Low Reynolds Number k- ϵ turbulence model
LES	Large-Eddy Simulations
MDKE	Modified k- ϵ turbulence model
MEE	Miao E- ϵ turbulence model
MMM	Mesoscale Meteorological Models
MRT	Mean radiant temperature ($^{\circ}\text{C}$)

NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
ω (TDR)	Turbulence Dissipation Rate (m^2/s^3)
PC	Pollutant concentration (dimensionless) (PC)
PD	Pressure distribution
PET	Physiological equivalent temperature ($^{\circ}\text{C}$)
PMV	Predicted mean vote (dimensionless)
RANS	Reynolds-averaged Navier-Stokes
RH	Relative humidity (%)
Ri	Richardson number (dimensionless)
RKE	Realizable k- ϵ turbulence model
RNGKE	Re-Normalization Group k- ϵ turbulence model
SAI	Solar access index (dimensionless)
SET	Standard effective temperature ($^{\circ}\text{C}$)
SLSGS	Smagorinsky-Lilly Subgrid-scale
SPI	Statistical performance indicators
SR	Solar radiation (W/m^2)
SSTKW	Shear Stress Transport k- ω turbulence model
ST	Surface temperature ($^{\circ}\text{C}$) (ST)
STKE	Standard k- ϵ turbulence model
SVF	Sky View Factor (dimensionless)
TEP	Temperature of equivalent perception ($^{\circ}\text{C}$)
THI	Temperature-humidity index (dimensionless)
TSP	Thermal Sensation Perception (dimensionless)
UHI	Urban Heat Island
UN	United Nations
UTCI	Universal thermal climate index ($^{\circ}\text{C}$)
VR	Ventilation rate (l/minute)
WBGT	Wet black globe temperature ($^{\circ}\text{C}$)
WCI	Wind comfort index (dimensionless)
WV	Wind velocity (m/s)
WVF	Water vapor fraction (%)
WVV	Wind velocity vectors
WYI	Weighted Year Index (year)
YMEE	Yamada and Mellor E- ϵ turbulence model

UHI effect in particular and urban microclimate in general can yield a wide range of impacts on health and energy use and these impacts are not necessarily negative. For instance, UHIs can reduce building energy demand depending on the city [9], location within the same city [10], type of building [11,12] or meteorological conditions [13]. Knowledge of urban microclimate and its dependency on key physical parameters is important as input for urban designers, architects and engineers to design and plan built environments [14–21]. The inherent complexity

and multiscale character evidently requires a multiscale approach for its analysis.

Urban microclimate as a research topic has a long history. The paper by Mills [22] identifies the work by Luke Howard [6] as the starting point. Mills [17] specifies six distinct periods of urban microclimate studies based on the research methodology followed:

- 1) Since the 1900s: Observation of urban-rural temperature differences with conventional meteorological measurement devices;
- 2) Since the 1960s: Measurement of urban microclimate process variables such as turbulent heat exchanges and the use of statistical methods to document UHI intensity;
- 3) Since the 1970s: Use of early energy budget models for the physical explanation of the UHI effect, early use of computer modeling techniques;
- 4) Since the 1980s: Adoption of experimental approaches, scaled-physical models and flux measurements (e.g. latent heat flux, storage heat flux);
- 5) Since the 1990s: Understanding the relationships between real urban forms and their effect on urban microclimate, organized field projects;
- 6) Since the early 2000s: Development of realistic urban microclimate models and employment of new techniques for the analysis of urban microclimate.

As suggested by these six periods, nowadays, a wide range of approaches can be employed for urban microclimate studies. Mirzaei

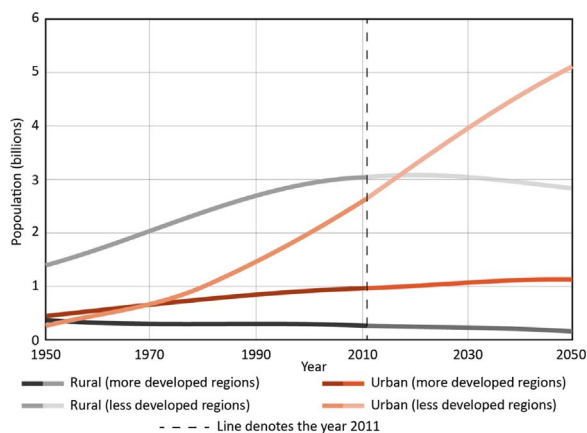


Fig. 1. World population in urban and rural areas. The dotted line denotes the year 2011. Figure modified from reference [3].

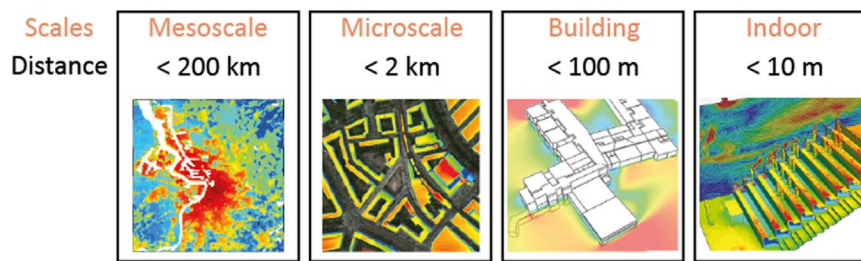


Fig. 2. Schematic representation of the spatial scales in climate modeling, with typical horizontal dimensions.

and Haghighat [15] and Mirzaei [23] distinguish two main categories: (a) observational approaches and (b) simulation² approaches. Observational approaches refer to measurement techniques such as field measurements, thermal remote sensing (e.g. satellite imagery) or small-scale physical modeling (e.g. atmospheric boundary layer wind-tunnel tests). Traditionally, observational approaches dominated urban microclimate analysis [24,25]. More recently, the increasing availability of computational resources has strongly advocated the application of numerical simulation approaches [26,27], where a distinction can be made between Energy Balance Models (EBM) and Computational Fluid Dynamics (CFD). The main advantage of the numerical simulation approaches compared with their observational counterparts is the opportunity to perform comparative analyses based on different scenarios [19,28]. In addition, while measurements are generally only performed at a limited number of points in space, numerical simulations can provide information on any investigated variable in the entire computational domain [16,24,29].

EBMs, which are based on the law of energy conservation for a control volume, have been used extensively in the past [30] and have increased in popularity with the pioneering article by Oke [31] entitled “The Energetic Basis of the Urban Heat Island”. Later, several studies utilized EBM for validation and model development purposes [32–38]. In the early 2000s, new validated models were proposed by Masson [39], Martilli et al. [40] and Kanda et al. [41]. Throughout this period of new EBM developments, the use of observational approaches, such as heat flux measurements, has continued [42–44], mostly to support the validation of newly developed models.

From an urban climate research point of view, CFD offers two advantages compared to EBM: (1) CFD is capable of performing simulations with the explicit coupling of velocity and temperature fields and if necessary, with the addition of humidity and pollution fields; (2) With CFD, it is possible to resolve the flow field at finer scales (e.g. building or even human scale) than EBM [45]. On the other hand, CFD simulations require a high-resolution representation of the urban geometry, the knowledge of boundary conditions for all relevant flow variables and adequate computational resources [15,16,19].

With the increased necessity for simulations incorporating higher spatial and modeling details and driven by the advances in computing power [27], CFD has continued to gain popularity as a tool for urban microclimate research, in particular from the 1990s. In the concluding chapters of two urban climate review papers by Souch and Grimmond [26] and Kanda [28], the increasing popularity of the CFD approach is pointed out with the following quotes:

“The development and use of CFD is a very active area of inquiry. The models are becoming more sophisticated in terms of numerical methods, mesh structures and turbulence modeling approaches.” (Souch and Grimmond [26]);

“CFD technologies that explicitly resolve urban buildings are the most complex representation of urban surfaces. Such technologies will play an important role not only in pure application studies but also in guiding the improvement of simpler models” (Kanda [28]).

² Here, the authors refer to numerical simulations, as opposed to physical simulations in e.g. atmospheric boundary layer wind tunnels.

Computational simulations can be employed to study urban microclimate at different spatial scales, ranging from the meteorological mesoscale over the meteorological microscale to the building scale and the indoor environment [16,19,29] (Fig. 2).

Numerical research at the meteorological mesoscale refers to climatic studies investigating atmospheric events, which occur within horizontal distances of a few to several hundred kilometers (e.g. thunderstorms) [46]. Numerical approaches at this scale are termed as Numerical Weather Prediction (NWP) models [29,47,48] or Mesoscale Meteorological Models (MMM) [49–51]. Urban climate analysis at the mesoscale can be traced back to the early 1970s and was mainly applied for 2D computational domains [52–57], investigating flow circulations occurring over urban areas, which were represented as localized heat sources. Later, mesoscale studies also included 3D applications for specific urban areas, such as St. Louis [58] and Chicago [59]. Nowadays, many urban climate studies at the meteorological mesoscale are being conducted [60–69] and some of the more recent efforts are focusing on coupling mesoscale climate models with finer scale models [50,51,70,71].

CFD at the meteorological microscale considers simulations at horizontal distances up to about 2 km [29,72]. CFD microscale simulations provide the possibility for the detailed modeling of every building and the parameterization of other obstacles within an urban area. Extensive reviews of CFD studies at the meteorological microscale were published in the past [16,19,29,73,74]. In recent years, with the advances in computational resources and the establishment of CFD best practice guidelines on the relevant topics (e.g. [19,75–79]), CFD studies at the meteorological microscale have gained popularity. CFD studies at the meteorological microscale can be used to investigate wind flow around buildings [45], pedestrian wind comfort [80–82], pedestrian thermal comfort [81], wind-driven rain [83,84], pollutant dispersion [85–90], snow drift [91,92] and other topics.

CFD can be utilized for the analysis of the microclimate around individual buildings, which is classified as the building scale with typical distances less than 100 m. There have been several review papers on CFD studies at the building scale [19,29,45,73,74,81]. Specifically, natural ventilation studies [93–96] and studies on Convective Heat Transfer Coefficients (CHTC) [97–100] are conducted at this scale. Many studies adopted a 2D modeling approach focusing on street canyons [101–118], on individual building shaped obstacles [119] or on vegetation cover [120–122]. For individual buildings, Building Energy Simulation (BES) is also employed for the analysis of indoor climate, indoor human thermal comfort and building energy consumption and recently, several studies have investigated the possibility for coupling CFD and BES models [123–126].

The smallest scale at which CFD is employed for climatic analysis in urban areas is the building indoor environment, where typical horizontal distances are around 10 m and the focus is on indoor climate. Studies at this scale have employed CFD mainly for ventilation studies [127–129] and for topics related to HVAC design and building services engineering [130]. Natural ventilation studies with CFD can also be performed at multiple scales, by combining building and indoor scales, which enables researchers to conduct coupled analyses [94,95,131–141].

Some review papers on the analysis of urban microclimate such as

Erell and Williamson [142], Ooka [143], Mochida et al. [51] and Lun et al. [144] have evaluated numerical models in general (including EBMs), without a specific focus on any CFD approach. Mochida and Lun [81] have reviewed CFD microclimate studies, but without focusing on the coupling of velocity and temperature fields. As CFD studies on urban microclimate are gaining popularity, it is important to document the achievements and trends in this field for future research, and this paper serves this purpose.

This paper reviews studies on the CFD analysis of urban microclimate. The scope of the review covers studies published in refereed journals, in English, with 3D computational domains and with coupling of velocity and temperature fields. To the best of our knowledge, the first study that fits to this scope is from 1998. Therefore, this review covers studies from what we consider as the first study in this field until the ones from 2015. In Section 2, the investigated studies are listed and classified based on the type of the urban area considered (generic versus real urban) and methodology followed (with or without validation study). Section 3 contains a further analysis of the reviewed studies and Section 4 presents a discussion with future perspectives. Finally, Section 5 contains the conclusions.

2. Overview of studies on the CFD analysis of urban microclimate

Within the above-mentioned scope of the review, a total of 183 studies are identified and investigated. The earliest study is from 1998 and the latest is from 2015. Fig. 3 shows the yearly distribution of the studies, indicating the increasing popularity of the field. The figure shows that the number of studies considered only in the last three years constitute more than half of all the studies (104 of 183 studies).

The papers are categorized based on the type of urban area (generic versus real) (see Fig. 4) and the methodology, without validation versus with validation. We remark that a study containing validation of at least one parameter from velocity and/or temperature field is classified as a study with validation. Fig. 5 shows that most studies are focused on real urban areas and are conducted without validation.

The studies are summarized in tables with the following entries:

- Author(s) and publication year;
- Reference number as listed in this paper;
- Urban setting/location
 - For studies with generic urban areas, the *urban geometries* are classified as follows (Fig. 6):
 - a) Building blocks: Multiple building blocks, distributed with a generic structure;
 - b) Street canyon: Only one street canyon;
 - c) Open space: No obstructions, possibly investigating additional features such as trees, water bodies etc.;
 - d) Urban street canyons: Multiple street canyons in an urban setting;
 - e) Courtyard: Domains focusing on a single courtyard.
 - For studies with real urban areas, the *urban location* is mentioned based on the information provided in the respective papers.
- Approximate form of the governing *equations solved* and the *turbulence model/sub-grid scale model* used. The investigated studies employed either Reynolds-averaged Navier Stokes (RANS) equations or Large Eddy Simulations (LES). The turbulence models (for RANS) and sub-grid scale models (for LES) employed are:
 - a) For RANS Abe-Kondoh-Nagano (AKN) k- ϵ [149] (AKNKE); Chen-Kim Extended k- ϵ (CKEKE) [150]; Durbin k- ϵ [151] (DKE); Eddy Diffusivity [101] (ED); Low Reynolds Number k- ϵ [149,152] (LRNKE); Miao E- ϵ [153] (MEE); Modified k- ϵ [131] (MDKE); Realizable k- ϵ [154] (RKE); Re-Normalization Group (RNG) k- ϵ [155] (RNGKE); Shear Stress Transport (SST) k- ω [156] (SSTKW); Standard k- ϵ [157] (STKE); Yamada and Mellor

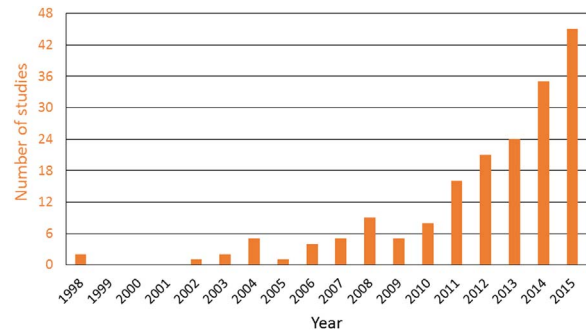


Fig. 3. The yearly distribution of the reviewed journal papers on CFD analysis of urban microclimate.

E- ϵ [158] (YMEE).

- b) For LES Deardorff Subgrid-scale [159] (DSGS); Smagorinsky-Lilly Subgrid-scale [160] (SLSGS).

– Validation/target parameters:

- a) Temperature related: Air temperature ($^{\circ}\text{C}$) (AT); Dry-bulb temperature ($^{\circ}\text{C}$) (DBT); Indoor air temperature ($^{\circ}\text{C}$) (IAT); Mean radiant temperature ($^{\circ}\text{C}$) (MRT); Surface temperature ($^{\circ}\text{C}$) (ST); Wet bulb globe temperature ($^{\circ}\text{C}$) (WBGT);
- b) Thermal comfort related: Physiological equivalent temperature ($^{\circ}\text{C}$) [161] (PET); Predicted mean vote (-) [162] (PMV) and Extended PMV (-) (EPMV) [163]; Standard effective temperature ($^{\circ}\text{C}$) [164] (SET); Temperature of equivalent perception ($^{\circ}\text{C}$) [165] (TEP); Thermal Sensation Perception (-) [166] (TSP); Universal thermal climate index ($^{\circ}\text{C}$) [167] (UTCI);
- c) Heat transfer related (includes radiation and reflectivity): Convective heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$) (CHTC); Heat flux (W/m^2) (HF); Sky View Factor (-) (SVF); Solar access index (-) (SAI); Solar radiation (W/m^2) (SR);
- d) Flow/ventilation related: Air change rate (1/hour) (ACH); Pressure (coefficient) (CP); Turbulent kinetic energy (m^2/s^2) (TKE); Turbulence dissipation rate (m^2/s^3) (TDR); Ventilation rate (l/minute) (VR); Wind velocity (m/s) (WV);
- e) Humidity/mass transfer related: Relative humidity (%) (RH); Water vapor fraction (%) (WVF);
- f) Dimensionless numbers/indices: Air quality index (-) (AQI); Froude number (-) (Fr); Richardson number (-) (Ri); Temperature-humidity index (-) (THI); Wind comfort index (-) (WCI);
- g) Other quantitative parameters: Building energy consumption (W) (BEC); Economy (currency) (ECN); Pollutant concentration (unit varies) (PC); Pressure distribution (PD); Statistical performance indicators (various, e.g. correlation coefficient) (SPI); Wind velocity vectors (WVV).

- *Keyword categories*: For every study, representative keywords are specified based on the list of keywords provided in each publication. Later, keywords with similar or interchangeable use are grouped and in total 37 keyword categories are identified.³ For papers with less than five keywords in the list of keywords, first the title and then the abstract is scanned for selecting suitable keyword categories. Referring to the title and the abstract for selecting keywords has its limitations but it was adopted due to the lack of a better alternative. Some very general keywords, such as microclimate, CFD and urban heat island (effect) are omitted from the categories. At the end, five keywords categories per study are identified. In the remainder of this paper, we will use the word “keyword” to refer to these “keyword categories”. In alphabetical order, the categories are:

³ For instance, various studies investigate the effect of building height, shape façade or roof on urban microclimate. Studies that use one of these as keywords are grouped in the keyword category called building form.

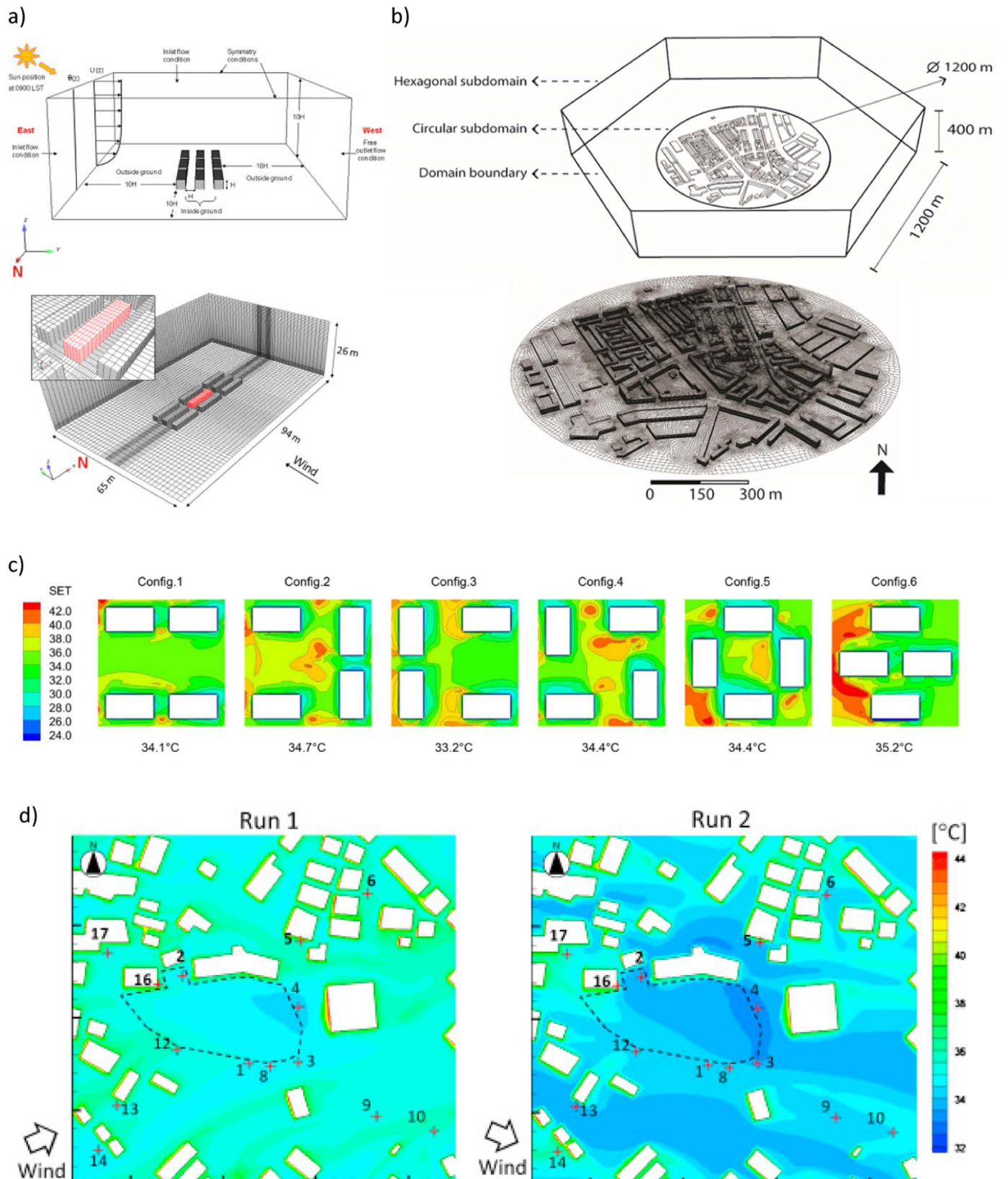


Fig. 4. Examples of CFD urban microclimate studies: a) Computational domain and grid for a generic urban domain [145]; b) Domain and grid for a real urban domain [146]; c) Contours of standard effective temperature inside a generic urban domain [147]; d) Contours of air temperature inside a real urban domain [148].

1. *Adaptation/mitigation*;
2. *Aspect ratio* (i.e. building height/street width);
3. *Building form* (i.e. height, roof, façade, shape);
4. *Canyon* (i.e. urban canyon, street canyon);
5. *Case comparison/case studies* (i.e. scenario analysis);
6. *(Convective) heat transfer coefficient* (CHTC);
7. *Climate* (i.e. climate scenarios, climate change, heat wave);
8. *Climate sensitive design* (i.e. bioclimatic design, climatic de-

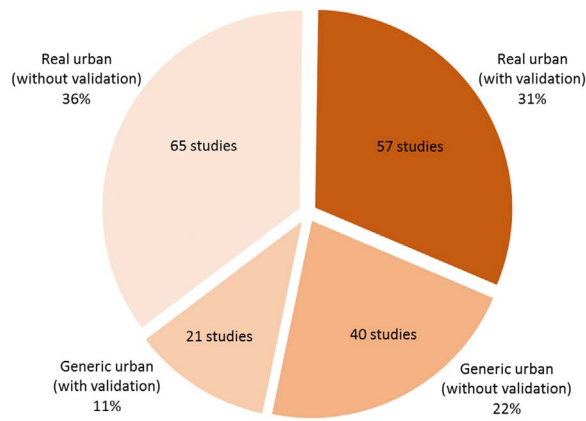


Fig. 5. Categorical distribution of the studies investigated in this paper. Categories are based on the type of urban area (generic vs. real) and on the methodology followed (with vs. without validation).

- sign);
9. *District comparison* (comparison of neighborhoods, streets, buildings in the same urban area);
 10. *Diurnal variation* (i.e. of temperature, velocity);
 11. *Economy* (i.e. feasibility, return of investment);
 12. *Energy* (i.e. building energy demand);
 13. *Energy budget* (i.e. Energy Balance Models);
 14. *Heat transfer* (i.e. modeling, convection, conduction);
 15. *Human/pedestrian*;
 16. *Materials/albedo* (i.e. absorptivity, reflectivity, conductivity);
 17. *Model coupling* (i.e. mesoscale – microscale, BES-CFD);
 18. *Model development* (i.e. new model, tool, software)
 19. *Optimization* (i.e. algorithms, parametric analysis);
 20. *Orientation*;
 21. *Pollutant dispersion*;
 22. *Radiation* (modeling) (i.e. reflections, solar, shading, SVF);
 23. *Seasonal variation* (i.e. temperature, relative humidity);
 24. *Specific forms* (i.e. courtyards, squares);
 25. *Statistical analysis* (i.e. regression, statistical performance indicators);
 26. *Surface heating* (i.e. heated facades, heated ground surfaces);
 27. *Sustainable/sustainability*;
 28. *Thermal comfort/heat stress*;
 29. *Thermal stability/instability*
 30. *Turbulent heat fluxes* (i.e. latent heat flux, storage heat flux, anthropogenic heat flux);
 31. *Urban density* (i.e. area density, building density);
 32. *Urban design/planning* (i.e. regulations, design competition, guidelines);

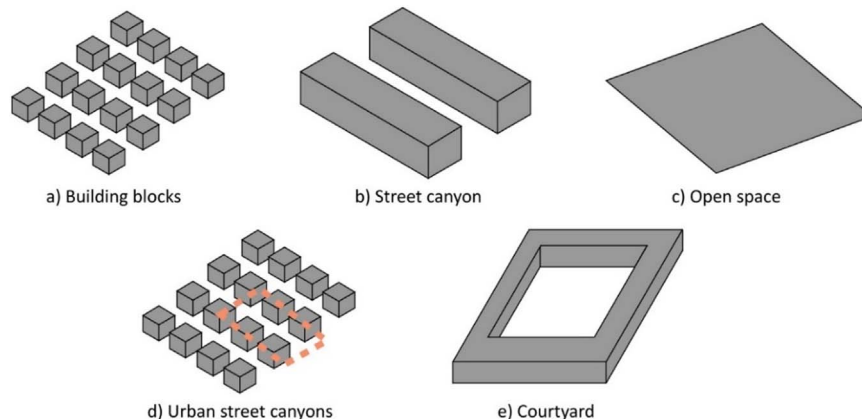


Fig. 6. Different urban geometries used in generic CFD studies.

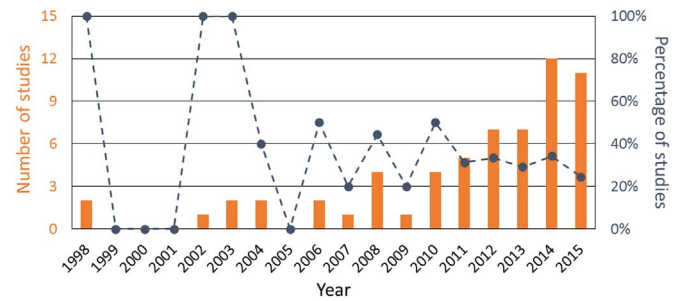


Fig. 7. Number of publications and percentage of studies for generic urban areas among all the papers investigated in this review.

33. *Urban forms/morphology* (i.e. building distribution, urban shape);
34. *Vegetation* (i.e. greenery, trees, urban parks, green roofs/facades);
35. *Ventilation* (i.e. pedestrian level ventilation);
36. *Water body* (i.e. water ponds, fountains);
37. *Wind/flow*.

2.1. Studies for generic urban areas

CFD studies for generic urban areas typically comprise simple building shapes, such as cubes or rectangular prisms. Early CFD models employed for microclimate analysis considered generic domains for model development and validation purposes. Later studies were generally conducted to investigate generic aspects of fluid flow and/or heat transfer in urban areas that can provide basic insights that subsequently can be translated to understanding these processes in real urban areas.

Fig. 7 depicts the number of publications and the percentage of studies for generic urban areas among all the papers investigated in this review. Generic urban areas in CFD microclimate analysis were quite popular in the early years of this field. Even though the number of publications of this sub-category kept increasing, with the development of new models and successful model validations, their share among all the studies seems to have declined in time. Of all publications reviewed in this paper, 61 of 183 (33.3%) studies focus on generic urban areas.

2.1.1. Studies without validation

Most early studies on generic urban areas did not consider validation. For example, this is the case for the five of the oldest studies in this review: Bruse and Fleer in 1998 [168], Herbert et al. in 1998 [169], Herbert and Herbert in 2002 [170], Dimoudi and Nikolopoulou in 2003 [171], and Baik et al. in 2003 [172]. The sub-category “generic urban areas – without validation” contains 40

Table 1
Overview of studies in the sub-category “generic urban areas - without validation”.

#	Authors (year)	Ref.	Urban setting	Equations / Models	Keywords	Parameters
1	Bruse and Fleer (1998)	[168]	Building blocks	RANS / YMEE	Model development, vegetation, heat transfer, urban form, wind	AT, WV
2	Herbert et al. (1998)	[169]	Street canyon	RANS / STKE	Material (albedo), seasonal variation, diurnal variation, canyon, energy budget	AT
3	Herbert and Herbert (2002)	[170]	Street canyon	RANS / STKE	Canyon, aspect ratio, energy budget, heat transfer, building form (height)	AT
4	Dimoudi and Nikolopoulou (2003)	[171]	Building blocks	Not specified	Vegetation, urban density, case comparison, radiation (SVF), orientation	AT
5	Balk et al. (2003)	[172]	Street canyon	RANS / ED	Heat transfer, canyon, pollutant dispersion, wind (flow), turbulent heat fluxes	AT, ST, WV
6	Robitu et al. (2004)	[173]	Open space (water pond)	RANS / STKE	Water body, heat transfer, building energy, turbulent heat fluxes, coupling	AT, ST, WV
7	Murakami (2004)	[174]	Building blocks	RANS / MDKE	Model development, urban morphology, vegetation, case comparison, thermal comfort	AT, MRT, SET
8	Ali-Toudert and Mayer (2006)	[175]	Street canyon	RANS / YMEE	Thermal comfort, aspect ratio, orientation, urban design, canyon	AT, SAL, PET
9	Murakami (2006)	[176]	Building blocks	RANS / MDKE	Model development, urban morphology, vegetation, case comparison, thermal comfort	AT, MRT, SET
10	Grignaffini and Vallati (2007)	[177]	Building blocks, open space	RANS / MDKE	Vegetation, climate (scenario analysis), urban morphology, materials, wind	AT, MRT, SET
11	Lin et al. (2008)	[178]	Building blocks	RANS / STKE	Vegetation, thermal comfort, urban form, pedestrian, case comparison	AT, ST
12	Chen et al. (2008)	[179]	Building blocks	Not specified	Optimization, vegetation, model development, thermal comfort, coupling	AT, RH, SET, MRT, WV
13	Zhao et al. (2008)	[180]	Urban street canyon	RANS / MDKE	Vegetation, wind, optimization, canyon, radiation (solar)	AT, MRT, SET, WV
14	Ooka et al. (2008)	[181]	Building blocks	RANS / ED	Aspect ratio, materials, orientation, building form (facades), canyon	ECN, SET, SVF
15	Dimitrova et al. (2009)	[182]	Urban street canyon	RANS / MDKE	Vegetation, optimization, thermal comfort, model development, economy	AT, WV
16	Okeil (2010)	[183]	Building blocks	RANS / YMEE	Canyon, wind, heat transfer, model development, building form (facades)	AT, WV
17	Hong et al. (2011)	[184]	Building blocks	RANS / STKE	Building form, energy (building), urban form, radiation (solar), vegetation	AT, WV
18	Park et al. (2012)	[185]	Street canyon	LES / DSGS	Vegetation, wind, optimization, canyon, radiation (solar)	AT, WV
19	Berkovic et al. (2012)	[186]	Courtyard	RANS / YMEE	Canyon, wind, heat transfer, surface heating, case comparison	AT, TKE, WV
20	Qu et al. (2012)	[145]	Building blocks	RANS / STKE	Thermal comfort, specific forms (courtyards), radiation (shading), orientation, case comparison	AT, PMV, RH, SR
21	Bo-ot et al. (2012)	[187]	Urban street canyon	RANS / STKE	Heat transfer, coupling, model development, radiation (solar), wind	AT, ST, TKE, WV
22	Mirzaei and Haghighat (2012)	[188]	Building blocks	RANS / STKE	Vegetation, energy (building), urban form, case comparison, optimization	AT, BEC, WV
23	Yang et al. (2012)	[189]	Building blocks	RANS / YMEE	Aspect ratio, material (albedo), building form (façade), thermal comfort, case comparison	AQI, THI, WCI
24	Lee et al. (2013)	[190]	Building blocks	RANS / RKE	Energy (building), urban form, vegetation, model coupling, case comparison	AT, BEC, IAT, RH, WT
25	Johansson et al. (2013)	[191]	Building blocks, open space	RANS / YMEE	Building form (height), urban form, ventilation, case comparison, wind	WV
26	Yahia and Johansson (2013)	[192]	Building blocks	RANS / YMEE	Building form (height), materials, vegetation, urban density, thermal comfort	AT, MRT, RH, ST, TEP, WV
27	Hong and Lin (2014)	[193]	Building blocks	RANS / STKE	Urban planning, aspect ratio, vegetation, orientation, thermal comfort	PET, ST
28	de Lieto Vollaro et al. (2014)	[194]	Street canyon	RANS / STKE	Urban morphology, vegetation, thermal comfort, ventilation, case comparison	AT, MRT, SET, VW, WV
29	Wang et al. (2014)	[195]	Urban street canyon	RANS / STKE	Canyon, radiation (solar), aspect ratio, model development, case comparison	AT, WV
30	Kim et al. (2014)	[196]	Urban street canyon	RANS / STKE	Canyon, wind, ventilation, heat transfer, building form (façade)	HF, PD, VR, WV
31	Perini and Magliocco (2014)	[197]	Building blocks	RANS / YMEE	Canyon, wind, vegetation, case comparison, building form (roof)	AT, TKE, WV, WV
32	Bottillo et al. (2014)	[198]	Street canyon	RANS / STKE	Urban density, aspect ratio, vegetation, thermal comfort, case comparison	AT, MRT, PMV
33	Yahia and Johansson (2014)	[199]	Building blocks	RANS / YMEE	Canyon, wind, heat transfer, solar radiation, model development	CHTC, RL, ST, WV
34	Ma et al. (2015)	[200]	Building blocks	RANS / DKE	Urban design, aspect ratio, vegetation, orientation, thermal comfort	PET, ST
35	Liu et al. (2015)	[201]	Building blocks	LES / SILSGS; RANS / RKE, SSTKW	Thermal comfort, statistical analysis, model development, pedestrians, diurnal variation	MRT, SET, WV
36	Hong and Lin (2015)	[147]	Building blocks	RANS / STKE	CHTC, energy (building), urban density, wind, model development	BEC, CHTC, ST
37	Allegri et al. (2015)	[202]	Building blocks	RANS / STKE	Urban form, vegetation, optimization, thermal comfort, pedestrian	PD, SET, WV
38	Liu et al. (2015)	[203]	Building blocks	Not specified	Energy (building), urban form / morphology, mitigation, case comparison, urban density	AT, BEC, ST, WV
39	Botham-Miynt et al. (2015)	[204]	Building blocks	RANS / STKE	Energy (building), climate, diurnal variation, model coupling, model development	AT, BEC, WV
40	Allegri et al. (2015)	[205]	Building blocks	RANS / STKE	Materials (albedo), building form, thermal comfort, urban morphology, pedestrian	AT
					Turbulent heat fluxes, energy (building), building form, ventilation, urban morphology	AT, HF, WV

Abbreviations: AKN k-e [149] (AKNNE); Chen-Kim Extended k-e (CKEKE) [150]; Deardorff Subgrid-scale [159] (DSGS); Durbin k-e [151] (DKE); Eddy Diffusivity [101] (ED); Low Reynolds Number k-e [149,152] (LRNKE); Miao E-e [153] (MEE); Modified k-e [131] (MDKE); Realizable k-e [154] (RKE); RNG k-e [155] (RNGKE); Smagorinsky-Lilly Subgrid-scale [160]; SST k- ω [156] (SSTKW); Standard k-e [157] (STKE); Yamada and Mellor E-e [158] (YMEE). Air change rate (l/hour) (ACH); Air quality index (-) (AQI); Air temperature (°C) (AT); Building energy consumption (W) (BEC); Convective heat transfer coefficient (W/m²K) (CHTC); Dry-bulb temperature (°C) (DBT); Economy (currency) (ECN); Froude number (-) (Fr); Heat flux (W/m²) (HF); Indoor air temperature (°C) (IAT); Mean radiant temperature (°C) (MRT); Physiological equivalent temperature (°C) (PET); Predicted mean vote (-) [162] (PMV); Extended PMV (-) (EPMV) [163]; Pressure (coefficient) (CP); Pollutant concentration (%) (PC); Pressure distribution (PD); Relative humidity (%) (RH); Richardson number (-) (Ri); Sky view factor (-) (SVF); Solar access index (-) (SAI); Solar radiation (W/m²) (SR); Standard effective temperature (°C) [164] (SET); Statistical Performance Indicators (various, e.g. Correlation coefficient (SPD); Surface temperature (°C) (ST); Temperature-humidity index (-) (THI); Temperature of equivalent perception (°C) [165] (TEP); Thermal Sensation Perception [166] (TSP); Turbulence dissipation rate (m²/s²) (TDR); Turbulent kinetic energy (m²/s²) (TKE); Universal thermal climate index (°C) [167] (UTCI); Ventilation rate (l/minute) (VR); Water vapor fraction (%) (WV); Wet black globe temperature (°C) (WBGT); Wind comfort index (-) (WCI); Wind velocity (m/s) (WV); Wind velocity vectors (WVV).

Table 2
Overview of studies in the sub-category “generic urban areas – studies with validation”.

#	Authors (year)	Ref.	Urban setting	Equations / Models	Validation parameter	Keywords	Parameters
1	Gu et al. (2010)	[216]	Open space, street canyon	LES / SLSGS	WV	Vegetation, thermal stability, canyon, pollutant dispersion, surface heating	AT, WV
2	Li et al. (2010)	[217]	Street canyon	LES / SLSGS	Ri	Surface heating, canyon, thermal stability, pollutant dispersion, flow	AT, PC, Ri, WV
3	Mirzaei and Haghighat (2010)	[218]	Building blocks, urban street canyon	RANS / STKE	WV	Ventilation, mitigation, thermal comfort, pedestrian, thermal stability	AT, Ri, WV
4	Kwak et al. (2011)	[219]	Street canyon	RANS / RNGKE	ST	Canyon, diurnal variation, wind (flow), radiation, surface heating	AT, HF, ST, WV
5	Luo and Li (2011)	[220]	Building blocks	RANS / RNGKE and SSTKW	WV	Ventilation, wind (flow), canyon, surface heating, building form (height)	ACH, AT, WV
6	Qu et al. (2011)	[207]	Building blocks	RANS / STKE	ST	Coupling, model development, heat transfer, wind (flow), diurnal variation	CHTC, HF, ST
7	Haghighat and Mirzaei (2011)	[221]	Building blocks	RANS / RNGKE	AT, WV	Surface heating, thermal stability, ventilation, material (albedo), canyon	AT, PC, WV
8	Pillai and Yoshie (2012)	[215]	Building blocks	RANS / LRNKE	AT, HF, WV	CHTC, urban form, building form (height), case comparison, urban density	AT, CHTC, HF, WV
9	Mirzaei and Carmeliet (2013)	[208]	Building blocks	RANS / RNGKE	WV	Canyon, wind, model development, case comparison, orientation	ST, WV
10	Vidrih and Medved (2013)	[209]	Open space (urban park)	RANS / RNGKE	AT	Vegetation, urban density, climate, case comparison, model development	AT
11	Pillai and Yoshie (2013)	[214]	Building blocks	RANS / LRNKE	HF	CHTC, flow, thermal stability, surface heating, case comparison	AT, CHTC, HF
12	Liu et al. (2013)	[210]	Building blocks	LES / SLSGS; RANS / SSTKW, RKE	CHTC, ST	CHTC, urban density, building energy, model development, case comparison	CHTC, ST, WV
13	Yaghoobian et al. (2014)	[222]	Street canyon	LES / DSGS	Fr, WV	Diurnal variation, wind(flow), canyon, thermal stability, material (albedo)	Fr, HF, PD, ST, TKE, WV
14	Taleghani et al. (2014)	[223]	Building blocks, courtyards	RANS / YMEE	AT	Thermal comfort, orientation, urban form, case comparison, specific forms (courtyards)	AT, MRT, PET, WV
15	Qaid and Ossen (2014)	[224]	Street canyon	RANS / YMEE	AT	Aspect ratio, building form (height), climate (hot and arid), diurnal variation, case comparison	AT, ST, WV
16	Bottillo et al. (2014)	[211]	Street canyon	RANS / STKE	AT, WV	Canyon, radiation, model development, heat transfer, wind (flow)	AT, CHTC, ST, WV
17	Santiago et al. (2014)	[212]	Street canyon	RANS / STKE	AT, WV	Radiation (solar), orientation, heat transfer, wind (flow), model development	AT, WV
18	Nazarian and Kleissl (2015)	[225]	Building blocks	RANS / RKE	ST	Material (albedo), aspect ratio, heat transfer, canyon, diurnal variation	HF, SR, ST, WV
19	Ghaffarianhoseini et al. (2015)	[226]	Courtyards	RANS / YMEE	DBT	Thermal comfort, building form, albedo, vegetation, specific forms (courtyards)	AT, DBT, MRT, PET, PMV, RH
20	Xue et al. (2015)	[213]	Open space (water body)	RANS / STKE	DBT, RH	Water body, heat transfer, model development, wind (flow), adaptation	DBT, RH
21	Yumino et al. (2015)	[206]	Building blocks	RANS / DKE	HF, ST	Adaptation / mitigation, climate, vegetation, materials (albedo), building form	BEC, HF, MRT, SET, ST, WBGT

Abbreviations: AKN k-e [149] (AKNKE); Chen-Kim Extended k-e (CKEKE) [150]; Deardorff Subgrid-scale [159] (DSGS); Durbin k-e [151] (DKE); Eddy Diffusivity [101] (ED); Low Reynolds Number k-e [149,152] (LRNKE); Miao E-e [153] (MEE); Modified k-e [131] (MDKE); Realizable k-e [154] (RKE); RNG k-e [155] (RNGKE); Smagorinsky-Lilly Subgrid-scale [160]; SST k- ω [156] (SSTKW); Standard k-e [157] (STKE); Yamada and Mellor E-e [158] (YMEE). Air change rate (1/hour) (ACH); Air quality index (-) (AQI); Air temperature ($^{\circ}\text{C}$) (AT); Building energy consumption (W) (BEC); Convective heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$) (CHTC); Dry-bulb temperature ($^{\circ}\text{C}$) (DBT); Economy (currency) (ECN); Froude number (-) (Fr); Heat flux (W/m^2) (HF); Indoor air temperature ($^{\circ}\text{C}$) (IAT); Mean radiant temperature ($^{\circ}\text{C}$) (MRT); Physiological equivalent temperature ($^{\circ}\text{C}$) [161] (PET); Predicted mean vote (-) [162] (PMV); Extended PMV (-) (EPMV) [163]; Pressure (coefficient) (CP); Pollutant concentration (%) (PC); Pressure distribution (PD); Relative humidity (%) (RH); Richardson number (-) (Ri); Sky view factor (-) (SVF); Solar access index (-) (SAI); Solar radiation (W/m^2) (SR); Standard effective temperature ($^{\circ}\text{C}$) [164] (SET); Statistical Performance Indicators (various, e.g. Correlation coefficient (SPD); Surface temperature ($^{\circ}\text{C}$) (ST); Temperature-humidity index (-) (THI); Temperature of equivalent perception ($^{\circ}\text{C}$) [165] (TEP); Thermal Sensation Perception [166] (TSP); Turbulence dissipation rate (m^2/s^3) (TDR); Turbulent kinetic energy (m^2/s^2) (TKE); Universal thermal climate index ($^{\circ}\text{C}$) [167] (UTC); Ventilation rate (l/minute) (VR); Water vapor fraction (%) (WVF); Wet black globe temperature ($^{\circ}\text{C}$) (WBGT); Wind comfort index (-) (WCI); Wind velocity (m/s) (WV); Wind velocity vectors (WVV).

studies, which are summarized in Table 1.

Most early studies focused on new model developments, demonstrating the suitability of CFD for microclimate analysis. For instance, the study by Bruse and Fleer [168] focused on surface, plant and air interaction at the microscale and is considered as the original documentation of the CFD microclimate software ENVI-Met, which is a tool increasingly employed by researchers in later years.

In the late 1990s, EBMs were the main tool used for the numerical analysis of urban microclimate. In the early years of CFD microclimate analysis, the influence of EBM methodology on CFD simulations is evidenced in the following ways: (1) CFD studies have averaged most of the turbulent heat fluxes in urban canopies similar to the way they were used in EBMs [169,170,172,173]; (2) the terms, which were popular in EBMs, such as “energy budget” and “turbulent heat fluxes,” were very often used as the main keywords in these early CFD studies.

The five most commonly used keywords in this sub-category are vegetation (19 of 40 studies), thermal comfort (16 of 40 studies), case comparison (15 of 40 studies), wind (flow) (12 of 40 studies) and canyon (12 of 40 studies). Keywords such as climate sensitive design, sustainable and thermal stability do not occur as keywords in any of these studies.⁴

2.1.2. Studies with validation

Validation of CFD studies for generic urban areas is typically performed with data from wind-tunnel measurements [15,19] whereas validation with field measurements is less common [206]. Many studies have been performed on the CFD validation of urban flow patterns in terms of velocity fields [29] but these studies are often conducted for isothermal conditions and as such are not within the scope of this review. As mentioned at the beginning of this section, a study is considered “with validation” as long as there is at least one parameter related to velocity or temperature fields, which is compared with measurement data. The sub-category “generic urban areas – with validation” contains 21 studies, which are summarized in Table 2.

Some of the validation studies are conducted to investigate and demonstrate the suitability and accuracy of newly developed CFD approaches [207–213]. Others focus on the CHTC of individual buildings in urban areas [210,214,215], which in turn can be used for coupling CFD with BES [210]. Validation studies on generic urban areas can be the first step towards justification of a CFD approach in modeling the cooling effect of adaptation measures, before implementing the same approach on real urban areas. Some of the studies for instance propose validated approaches for the cooling effect from vegetation sources [209] and from water bodies [213] on generic urban domains.

The five most commonly used keywords in this sub-category are wind (flow) (10 of 21 studies), canyon (9 of 21 studies), case comparison (7 of 21 studies), model development (7 of 21 studies) and surface heating (6 of 21 studies). Note however that keywords such as climate sensitive design, energy budget, optimization, seasonal variation, sustainability and urban design do not occur as keywords in any of these 21 studies.⁵

2.2. Studies for real urban areas

The term “real urban areas” can cover only a few buildings to a portion of a city. CFD simulations on real urban areas are performed either as practical case studies or – in case of studies with validation – to investigate the possibilities and limitations of CFD for real urban areas that are generally characterized by a complexity that substantially exceeds that of generic urban areas.

⁴ Although these words might be used within the text itself, here, they are not present in the keyword categories as extracted from abstract and the list of keywords.

⁵ Although these words might be used within the text itself, here, they are not present in the keyword categories as extracted from the abstract and the list of keywords.

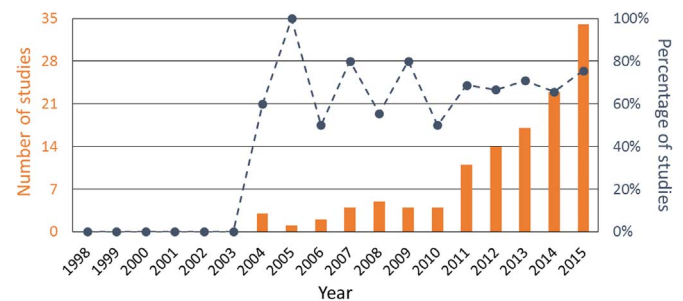


Fig. 8. Number of publications and percentage of studies for real urban areas among all the papers investigated in this review.

Fig. 8 depicts the number of publications and the percentage of studies for real urban areas among all the papers investigated in this review. The number of publications for real urban areas has been rapidly increasing especially in the last five years. Of all the publications reviewed in this paper, 122 of 183 (66.6%) studies focus on real urban areas.

2.2.1. Studies without validation

CFD studies on real urban areas without validation are generally comparative studies, where several urban configurations, design parameters, neighborhoods (districts) within the same urban area are compared. Most of these studies aim to reach best-case scenarios based on the optimization of a target parameter (e.g. outdoor thermal comfort). The sub-category “real urban areas – without validation” contains 65 studies, rendering this sub-category the most popular one. These studies are summarized in Table 3.

The table indicates that studies in this sub-category have two characteristics. First, all studies are conducted using the RANS equations, which may be attributed to the high computational requirements of LES. Second, most studies are characterized by practical rather than fundamental keywords. The five most commonly used keywords in this sub-category are vegetation (39 of 65 studies), case comparison (36 of 65 studies), thermal comfort/heat stress (29 of 65 studies), urban design/planning (27 of 65 studies) and materials/albedo (19 of 65 studies). Keywords which might indicate that a particular study's focus is on fundamental aspects, such as CHTC, heat transfer or wind (flow), are not used often (1 of 65, 2 of 65 and 9 of 65 studies respectively). Keywords such as energy budget, optimization, statistical analysis, surface heating and thermal stability do not occur as keyword⁶ in any of these 65 studies.

2.2.2. Studies with validation

Validation of CFD studies for real urban areas is typically performed with data from on-site (field) measurements. Wind-tunnel measurements focusing on real urban areas can be challenging as the representative models of real, complex urban formations are more difficult (and often more expensive) to build than generic forms and they are often larger, hence might be difficult to fit into a wind tunnel.

Similar to CFD in general and for CFD studies on urban microclimate, verification and validation are essential actions towards accurate and reliable results [16,29,45,74–77,80,82,86,128,292–304]. Even in today's era of numerical climate models, new field measurements are being conducted for this purpose [17,305].

CFD urban microclimate studies in the sub-category “real urban areas – with validation” include validation based on one or more of the simulation parameters with measurements. We note that studies on the CFD validation of urban flow patterns in terms of velocity fields are often conducted for isothermal conditions and as such are not within the scope of this review. For real urban areas, the field measurement of

⁶ Although these words might be used within the text itself, here, they are not present in the keyword categories as extracted from the abstract and the list of keywords.

Table 3
Overview of studies in the sub-category “real urban areas – without validation”.

#	Authors (year)	Ref.	Location (Country)	Equations / Models	Keywords	Parameters
1	Fang et al. (2004)	[227]	Fangzhuang, Beijing (China)	RANS / MEE	Urban planning, coupling (mesoscale - microscale), model development, vegetation, water body	ST, WV
2	Robitu et al. (2006)	[228]	Fleuriot Square, Nantes (France)	RANS / STKE	Vegetation, water body, thermal comfort, model development, case comparison	MRT, PMV, ST, WV
3	Yu and Hien (2006)	[229]	Bukit Batok Nature Park and Clementi Woods Park (Singapore)	RANS / YMEE	Vegetation, district comparison, case comparison, diurnal variation, urban form	AT
4	Wong et al. (2007)	[230]	National University of Singapore (Singapore)	RANS / YMEE	Vegetation, urban form, case comparison, diurnal variation, materials	AT
5	Li and Yu (2008)	[231]	Wuhan City (China)	Not specified	Urban planning, water body, vegetation, building form (height), model development	AT, ST
6	Huang et al. (2008)	[232]	Kawasaki City (Japan)	RANS / STKE	Pollutant dispersion, diurnal variation, turbulent heat fluxes, wind, heat transfer	AT, ST, WV
7	Andrade and Alcoforado (2008)	[233]	Telheiras, Lisbon (Portugal)	RANS / YMEE	Thermal comfort, urban form, seasonal variation, district comparison, radiation (SVF)	AT, MRT, PET
8	He and Hoyano (2009)	[234]	Tonami (Japan)	RANS / AKNKE	Thermal comfort, coupling, model development, materials, vegetation	AT, MRT, SET, WV
9	Chen et al. (2009)	[235]	Otemachi and Kyobashi (Japan)	RANS / STKE	Mitigation, thermal comfort, turbulent heat fluxes, district comparison, case comparison	AT, WV
10	Fahmy and Sharples (2009)	[236]	5th Community, Cairo (Egypt)	RANS / YMEE	Vegetation, urban form, aspect ratio, building density	PMV
11	Fahmy et al. (2010)	[237]	Misr Al-Gadida, Cairo (Egypt)	RANS / YMEE	Vegetation, surface fluxes, radiation, diurnal variation, district comparison	AT, MRT, RH
12	Hsieh et al. (2010)	[238]	Tokyo (Japan)	RANS / STKE	Material (albedo), wind, water body, vegetation, urban planning	AT, ST, WV
13	Al-Sallal and Al-Rais (2011)	[239]	Al-Ras, Dubai (United Arab Emirates)	RANS / STKE	Ventilation, urban form, canyon, model development, seasonal variation	AT, WV
14	Ashie and Kono (2011)	[240]	Nihonbashi, Tokyo (Japan)	RANS / STKE	Urban design, case comparison, wind, climate-sensitive design, coupling (mesoscale - microscale)	AT, WV
15	Bouyer et al. (2011)	[241]	Lyon (France)	RANS / STKE	Energy (building), vegetation, urban design, coupling, materials	AT, BEC
16	Fintikakis et al. (2011)	[242]	Tirana (Albania)	RANS / STKE	Climate sensitive design, materials, vegetation, thermal comfort, case comparison	AT, ST, WV
17	Kaoru et al. (2011)	[243]	Osaka City (Japan)	RANS / STKE	Radiation, diurnal variation, case comparison, model development, coupling	AT, ST, WV
18	Fahmy and Sharples (2011)	[244]	5th Community, Cairo (Egypt)	RANS / YMEE	Urban design, case comparison, thermal comfort, urban form, urban density	AT, PMV
19	Symnefa et al. (2011)	[245]	Ag. Paraskevi, Athens (Greece)	RANS / STKE	Materials (albedo), radiation (reflections), mitigation, diurnal variation, urban design	AT
20	Bouhabla and Alkama (2012)	[246]	Street of the Republic, Biskra (Algeria)	RANS / YMEE	Vegetation, heat transfer, case comparison, urban form, diurnal variation	AT, RH, SR, WV
21	Al-Sallal and Al-Rais (2012)	[247]	Al-Mankhool, Dubai (United Arab Emirates)	RANS / STKE	Ventilation, urban form, canyon, thermal comfort, seasonal variation	AT, WV
22	Lenzholzer (2012)	[248]	Grote Markt, Groningen (Netherlands)	RANS / YMEE	Urban design, case comparison, thermal comfort, specific forms (squares), vegetation	PMV
23	Tominaga (2012)	[249]	Niigata City (Japan)	RANS / DKE	Urban form, building form (height), ventilation, case comparison, wind	ACH, AT, WV
24	Baik et al. (2012)	[250]	Central Region, Seoul (South Korea)	RANS / RKGKE	Building form (roof), vegetation, canyon, urban density, case comparison	AT, PC
25	Carfan et al. (2012)	[251]	Consolacao and Fontes do Ipiranga State Park, Sao Paulo (Brazil)	RANS / YMEE	Thermal comfort, adaptation, materials, district comparison, building form (height)	MRT, PMV, WV
26	Stavrakakis et al. (2012)	[252]	Gazi, Heracion (Greece)	RANS / STKE	Climate-sensitive design, thermal comfort, specific forms (squares), vegetation, diurnal variation	AT, EPMV, ST
27	Palme and Ramirez (2013)	[253]	Avenida Brasil, Antofagasta (Chile)	RANS / YMEE	Urban design, vegetation, sustainability, climate (dry and arid), radiation (SVF)	AT, MRT, SVF, WV
28	Maragkogiannis et al. (2013)	[254]	1866 Square, Chania (Greece)	RANS / CKEKE	Case comparison, materials, thermal comfort, climatic design, specific forms (squares)	AT, ST, WV
29	Dütemeyer et al. (2013)	[255]	Elisabeth-Stift Erle, Gelsenkirchen (Germany)	RANS / YMEE	Thermal comfort, adaptation, vegetation, urban planning, climate (future scenarios)	AT, PET, WV
30	Declet-Barreto et al. (2013)	[256]	The Latino Urban Core, Phoenix (USA)	RANS / YMEE	Vegetation, climate (heat wave), mitigation, urban design, case comparison	AT, ST
31	Taleb and Hilleh (2013)	[257]	Jumairah and Bastakiyah, Dubai (United Arab Emirates)	RANS / YMEE	Urban design, case comparison, urban form, seasonal variation, wind	AT, SVF, WV
32	Egerhazi et al. (2013)	[258]	Szeged (Hungary)	RANS / YMEE	Seasonal variation, diurnal variation, thermal comfort, radiation (shading), vegetation	PET
33	Radhi et al. (2013)	[259]	Amwaj Islands and Wadi Al-Sail (Bahrain)	RANS / RKGKE	District comparison, wind, thermal comfort, urban density, urban form	AT, PMV, WV (continued on next page)

Table 3 (continued)

#	Authors (year)	Ref.	Location (Country)	Equations / Models	Keywords	Parameters
34	Miao et al. (2013)	[260]	Zhongguancun, Beijing (China)	RANS / STKE	Coupling, pollutant dispersion, wind, diurnal variation, model development	AT, TKE, WV
35	Frohlich and Matzarakis (2013)	[261]	The Place of the Old Synagogue, Freiburg (Germany)	RANS / YMEE	Radiation (SVF), case comparison, thermal comfort, urban design, specific forms (squares)	PET, SVF
36	Egerhazi et al. (2013)	[262]	Szeged (Hungary)	RANS / YMEE	Materials, vegetation, water body, urban design, case comparison	MRT, PMV
37	Tiwary and Kumar (2014)	[263]	Not mentioned	RANS / YMEE	Vegetation, seasonal variation, wind, materials (albedo), pollutant dispersion	AT, RH, WV
38	Taleb and Taleb (2014)	[264]	Dubai International Academic City, Dubai (United Arab Emirates)	RANS / YMEE	Thermal comfort, urban planning, orientation, case comparison, vegetation	AT, MRT, PMV, RH, WV
39	Ambrosini et al. (2014)	[265]	Old town, Teramo (Italy)	RANS / YMEE	Building form (roof), vegetation, materials (albedo), case comparison, diurnal variation	AT, RH, WV
40	Gros et al. (2014)	[266]	Pin Sec district, Nantes (France)	RANS / STKE	Materials (albedo), case comparison, energy (building), coupling, model development	AT, BEC, ST
41	Ketterer and Matzarakis (2014)	[267]	City center, Stuttgart (Germany)	RANS / YMEE	Thermal comfort, model development, vegetation, case comparison, urban planning	AT, PET
42	Ketterer and Matzarakis (2014)	[268]	Stuttgart-West, Stuttgart (Germany)	RANS / YMEE	Urban planning, case comparison, vegetation, aspect ratio, orientation	AT, MRT, SVF, WV
43	Yi and Peng (2014)	[269]	Weston Park, Sheffield (England)	RANS / YMEE	Climate (future scenarios), case comparison, energy (building), coupling, thermal comfort	AT, BEC, SR
44	Peng and Elwan (2014)	[270]	New Cairo, Cairo (Egypt); Sheffield University Campus, Sheffield (England)	RANS / YMEE	Climate (future scenarios), energy (building), coupling, urban design, case comparison	AT, MRT, RH, WV
45	Lehmann et al. (2014)	[271]	Inner city, Dresden (Germany)	RANS / YMEE	Vegetation, urban form, adaptation, climate (change), urban design	AT
46	Ciamarella et al. (2014)	[272]	CityLife urban district and Milan, Milan (Italy)	RANS / YMEE	District comparison, thermal comfort, urban design, urban form, seasonal variation	AT, PC
47	Taleghani et al. (2014)	[273]	Portland State University, Portland (USA)	RANS / YMEE	Specific forms (courtyards), water body, materials (albedo), mitigation, thermal comfort	AT, MRT
48	Sodoudi et al. (2014)	[274]	6th urban district, Tehran (Iran)	RANS / YMEE	Materials (albedo), vegetation, case comparison, mitigation, urban density	AT, RH
49	Gromke et al. (2015)	[275]	City center, Arnhem (Netherlands)	RANS / RKE	Vegetation, adaptation, climate (heat wave), building form (façade, roof), case comparison	AT, WV
50	Djukic et al. (2015)	[276]	Central zone, Leskovac (Serbia)	RANS / YMEE	Climate sensitive design, urban design, specific forms (squares), vegetation, case comparison	AT
51	Tsilini et al. (2015)	[277]	Chalepa, Chanie (Greece)	RANS / YMEE	Vegetation, case comparison, seasonal variation, bioclimatic design, urban design	AT, ST
52	Peng et al. (2015)	[278]	Dazhimen neighborhood, Wuhan City (China)	RANS / RKE	Urban planning, case comparison, urban form, sustainability, thermal comfort	ST, WV
53	O'Malley et al. (2015)	[279]	West Kensington (Seagrave Site), London (England)	RANS / YMEE	Vegetation, materials (albedo), water body, case comparison, urban design	AT, ST
54	Peng et al. (2015)	[280]	Old district, Wuhan City (China)	RANS / RKE	Urban form, urban design, thermal comfort, radiation (solar), wind	AT, ST, WV
55	Conry et al. (2015)	[281]	Chicago Metropolitan Area, Chicago (USA)	RANS / YMEE	Coupling, energy (building), seasonal variation, climate (change), model development	BEC, MRT, PMV
56	Middel et al. (2015)	[282]	The City of Phoenix, Phoenix (USA)	RANS / YMEE	Vegetation, materials (albedo), climate (future scenarios), building form (roof), mitigation	AT
57	Peng et al. (2015)	[283]	Wuhan (China)	RANS / RKE	case comparison, urban design / planning, pedestrian, thermal comfort, ventilation	ST, WV
58	Salata et al. (2015)	[284]	Rome (Italy)	RANS / YMEE	thermal comfort, mitigation, vegetation, materials (albedo), specific forms (courtyard)	AT, MRT, PMV
59	Yang et al. (2015)	[285]	Taipei (Taiwan)	RANS / RKE	case comparison, thermal comfort, urban design, vegetation, specific forms (squares)	AT, WV
60	An et al. (2015)	[286]	Hong Kong (China)	RANS / YMEE	case comparison, water body, vegetation, district comparison, sustainability	AT
61	Wang et al. (2015)	[287]	Toronto (Canada)	RANS / YMEE	Vegetation, materials (albedo), district comparison, mitigation, urban form	AT, MRT, ST
62	Cao et al. (2015)	[288]	Guangzhou (China)	Not specified	Orientation, thermal comfort, urban design, ventilation, materials (albedo)	AT, WV

(continued on next page)

Table 3 (continued)

#	Authors (year)	Ref.	Location (Country)	Equations / Models	Keywords	Parameters
63	Lobaccaro et al. (2015)	[289]	Bilbao (Spain)	RANS / YMEE	Canyon, vegetation, thermal comfort, case comparison, aspect ratio	AT, MRT, PET, RH, ST, WV
64	Radhi et al. (2015)	[290]	Amwaj islands (Bahrain)	RANS / RNGKE	energy (building), thermal comfort, urban design, vegetation, water body	AT, BEC, MRT, PMV, WV
65	Girgis et al. (2015)	[291]	Cairo (Egypt)	RANS / YMEE, STKE	turbulent heat fluxes, case comparison, CHTC, thermal comfort, specific forms (square)	AT, ST

Abbreviations: AKN k-ε [149] (AKNNE); Chen-Kim Extended k-ε (CKEKE) [150]; Deardorff Subgrid-scale [159] (DSGS); Durbin k-ε [151] (DKE); Eddy Diffusivity [101] (ED); Low Reynolds Number k-ε [149,152] (LRNKE); Miao E-ε [153] (MEE); Modified k-ε [131] (MDKE); Realizable k-ε [154] (RKE); RNG k-ε [155] (RNGKE); Smagorinsky-Lilly Subgrid-scale [160]; SST k-ε [157] (STKE); Yamada and Mellor E-ε [158] (YMEE). Air change rate (l/hour) (ACH); Air quality index (-) (AQI); Air temperature (°C) (AT); Building energy consumption (W) (BEC); Convective heat transfer coefficient (W/m²K) (CHTC); Dry-bulb temperature (°C) (DBT); Economy (currency) (ECN); Froude number (-) (Fn); Heat flux (w/m²) (HF); Indoor air temperature (°C) (IAT); Mean radiant temperature (°C) (MRT); Physiological equivalent temperature (°C) [161] (PET); Predicted mean vote (-) [162] (PMV); Extended PMV (-) (EPMV) [163]; Pressure (coefficient) (CP); Pollutant concentration (%) (PC); Pressure distribution (PD); Relative humidity (%) (RH); Richardson number (-) (RD); Sky view factor (-) (SVF); Solar access index (-) (SAD); Solar radiation (W/m²) (SR); Standard effective temperature (°C) [164] (SET); Statistical Performance Indicators (various, e.g. Correlation coefficient)(SPD); Surface temperature (°C) (ST); Temperature-humidity index (-) (THI); Temperature of equivalent perception (°C) [165] (TEP); Thermal Sensation Perception [166] (TSP); Turbulence dissipation rate (m²/s³) (TDR); Turbulent kinetic energy (m²/s²) (TKE); Universal thermal climate index (°C) [167] (UTCI); Ventilation rate (l/minute) (VR); Water vapor fraction (%) (WVF); Wet black globe temperature (°C) (WBGT); Wind comfort index (-) (WCI); Wind velocity (m/s) (WV); Wind velocity vectors (WVV).

air temperature is relatively straightforward and especially in the last years, many campaigns are undertaken for measurement data, although the suitability and availability of these data for scientific use and especially for validation can be a limitation. The reason is that the complexity and inherent variability of the meteorological conditions not only require careful measurement of a large number of parameters (to be used as boundary conditions in the simulations) but also a very complete reporting of urban area, measurement set-up, measurement accuracy, etc., without which a detailed and thorough validation exercise will not be possible [296,301,306,307]. The sub-category “real urban areas – with validation” contains 57 studies, 47 of which use air temperature as one of the validation parameters. The studies belonging to this sub-category are summarized in Table 4.

Similar to the studies on real urban areas without validation, all the studies in this sub-category employed the RANS equations. However, different from the studies without validation, studies in this sub-category have radiation as a relatively popular keyword (16 of 57 studies). That is mostly because recent studies on human thermal comfort demonstrated the importance of thermal radiation (e.g. mean radiant temperature) on thermal comfort levels. Therefore, studies try to validate their CFD simulation results based on radiation parameters.

The five most commonly used keywords in this sub-category are thermal comfort/heat stress (29 of 57 studies), vegetation (28 of 57 studies), materials/albedo (19 of 57 studies), case comparison (20 of 57 studies) and radiation (16 of 57 studies). On the other hand, keywords such as energy budget, economy, optimization, surface heating and thermal stability do not occur as keywords⁷ in any of these 57 studies.

3. Comparative analysis of CFD studies on urban microclimate

3.1. Urban setting/location investigated

Considering generic urban areas, five studies in this sub-category [177,191,216,218,223] considered more than one type of urban setting. The majority of generic studies focused on generically distributed building blocks (36 of 61 studies, or 59.0%), followed by street canyons (15 of 61 studies, or 24.6%), open spaces (6 of 61 studies, or 9.8%), urban street canyons (6 of 61 studies, or 9.8%) and courtyards (3 of 61 studies, or 4.9%).

Studies for generically distributed building blocks are mostly case comparisons without validation and they focus on the effect of different urban geometries (e.g. orientation, density) [174,176, 178,189,197,223], vegetation patterns [171,193,199], building materials [188] and building forms [190,191]. Studies on building blocks that include validation are in most of the cases targeted at more fundamental fluid flow or heat transfer aspects [207,210, 214,215,225]. Studies for street canyons and urban street canyons typically investigate canyon related aspects, such as the effect of aspect ratio [175,180,194,224] and wind/ventilation [172,182,184, 185,195,196,222].

The majority of the studies on real urban areas are conducted for locations in mid-latitude climates and in the developed regions of the world (Fig. 9). Fig. 9 seems to indicate a lack of variety in the study locations. Although this review comprises 122 studies on real urban areas, the number of different cities in these studies is only 74 and the number of countries is only 30. Ranked according to the number of studies, the top five urban locations are Phoenix (USA) (7 studies), Hong Kong (China) and Cairo (Egypt) (both 6 studies), Tokyo (Japan) (5 studies) and Wuhan (China) (4 studies). Similarly, the top five countries are China (23 studies), Japan (12 studies), USA (11 studies), Germany (9 studies) and Greece (8 studies).

⁷ Although these words might be used within the text itself, here, they are not present in the keyword categories as extracted from the abstract and the list of keywords.

Table 4
Overview of studies in the sub-category “real urban areas – with validation.”.

#	Authors (year)	Ref.	Location (Country)	Equations / Models	Validation parameter	Keywords	Parameters
1	Takahashi et al. (2004)	[308]	Several locations in Kyoto City (Japan)	RANS / MDKE	ST	Turbulent heat fluxes, heat transfer, coupling, model development, diurnal variation	AT, ST
2	Chen et al. (2004)	[309]	Shenzhen City (China)	RANS / MDKE	ST	Heat transfer, thermal comfort, turbulent heat fluxes, building form (façade), coupling	AT, MRT, RH, SET, ST, WV
3	Huang et al. (2005)	[310]	Shinjuku Park Tower, Tokyo (Japan)	RANS / STKE	AT, WV	Coupling, model development, thermal comfort, pedestrians, heat transfer	AT, RH, SET, WV
4	Emmanuel and Fernando (2007)	[311]	Pettah, Colombo / Sri Lanka and Central Business District, Phoenix (USA)	RANS / YMEE	AT	Climate sensitive design, vegetation, urban density, materials (albedo), urban form	AT, MRT
5	Emmanuel et al. (2007)	[312]	Colombo (Sri Lanka)	RANS / YMEE	AT	Urban morphology, materials (albedo), vegetation, thermal comfort, radiation (shading)	AT, MRT, PET, ST
6	Ashie et al. (2007)	[313]	Central Tokyo, Tokyo (Japan)	RANS / STKE	AT	Wind, model development, building form (height), district comparison, materials	AT, WV
7	Yamaoka et al. (2008)	[314]	Mido-Suji Street, Osaka (Japan)	RANS / MDKE	AT	Canyon, water body, building form (height), materials, vegetation	AT, MRT, SET, WV
8	Priyadarsini et al. (2008)	[315]	Central Business District, Singapore (Singapore)	RANS / STKE	AT, WV	Building form (façade), materials, mitigation, canyon, aspect ratio	AT, WV
9	Kakon et al. (2009)	[316]	Motijheel, Dhanmondi, and Siddeswari, Dhaka (Bangladesh)	RANS / YMEE	AT	Canyon, diurnal variation, thermal comfort, urban density, urban planning	AT, RH, ST, SVF, THI, WV
10	Kakon et al. (2010)	[317]	Dhanmondi, Dhaka (Bangladesh)	RANS / YMEE	AT	Building form (height), thermal comfort, urban density, pedestrian, canyon	AT, MRT, RH, ST, SVF, THI, WV
11	Jeon et al. (2010)	[318]	Suwon (South Korea)	RANS / STKE	WV	Vegetation, materials, coupling, turbulent heat fluxes, radiation (shading)	AT, ST, WV
12	Krüger et al. (2011)	[319]	XV de Novembro Street, Curitiba (Brazil)	RANS / YMEE	WV	Thermal comfort, radiation (SVF), urban planning, wind (flow), urban form	MRT, SVF, WV
13	Yang et al. (2011)	[320]	Pudong New District, Shanghai (China)	RANS / YMEE	AT	Climatic design, materials (albedo), vegetation, thermal comfort, case comparison	AT, MRT, PET
14	Gaitani et al. (2011)	[321]	Messolongiout Square, Athens (Greece)	Not specified	AT, WV	Bioclimatic design, materials (albedo), vegetation, radiation (shading), case comparison	AT, WV
15	Chow et al. (2011)	[322]	Arizona State University Campus at Tempe, Phoenix (USA)	RANS / YMEE	AT	Material, vegetation, diurnal variation, urban form, orientation	AT
16	Chen and Ng (2012)	[323]	The Central Market, Hong Kong (China)	RANS / YMEE	AT, MRT	Thermal comfort, vegetation, urban planning, case comparison, pedestrians	AT, MRT, PET
17	Zhang et al. (2012)	[324]	The Hong Kong Polytechnic University Campus, Hong Kong (China)	RANS / RNGKE, STKE	PR	Ventilation, thermal comfort, orientation, seasonal variation, urban density	PR, PMV, WV
18	Chow and Brazel (2012)	[325]	Tempe and West Phoenix, Phoenix (USA)	RANS / YMEE	AT	Vegetation, case comparison, mitigation, sustainability, thermal comfort	AT, MRT
19	Liu et al. (2012)	[326]	Downtown Beijing (China)	LES / SLGS	AT, WV	Coupling, pollutant dispersion, wind, model development, heat transfer	AT, HF, WV
20	Shahidan et al. (2012)	[327]	Persiaran Perdana, Putrajaya (Malaysia)	RANS / YMEE	AT, ST	Urban design, mitigation, vegetation, energy (building), materials (albedo)	AT, BEC, ST
21	Ma et al. (2012)	[328]	Shenzhen (China)	RANS / DKE	ST, WV	Radiation (solar), pedestrian, model development, coupling, materials	AT, RH, ST, WV
22	Ng et al. (2012)	[329]	Tsuen Wan, Hong Kong (China)	RANS / YMEE	AT	Urban density, vegetation, aspect ratio, urban planning, case comparison	AT
23	Maras et al. (2013)	[330]	Aachen Central Station, Aachen (Germany)	RANS / YMEE	PMV	Heat stress, vegetation, urban density, specific forms (squares), case comparison	PMV
24	Yang et al. (2013)	[331]	Metropolitan Guangzhou / (China)	RANS / YMEE	AT, HF, ST	Radiation (solar), heat transfer, materials (albedo), heat fluxes, diurnal variation	AT, HF, RH, ST
25	Carnielo and Zinzi (2013)	[332]	Prati Neighborhood, Rome (Italy)	RANS / YMEE	ST	Materials (albedo), case comparison, energy (building), diurnal variation, radiation (reflections)	BEC, ST
26	Peng and Jim (2013)	[333]	Several locations in Hong Kong (China)	RANS / YMEE	AT	Vegetation, case comparison, sustainable, diurnal variation, thermal comfort	AT, PET, PMV

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Table 4 (continued)

#	Authors (year)	Ref.	Location (Country)	Equations / Models	Validation parameter	Keywords	Parameters
27	Müller et al. (2013)	[334]	Oberhausen (Germany)	RANS / YMEE	AT, RH	Adaptation, thermal comfort, vegetation, radiation (shading), water body	AT, RH, PET
28	Goldberg et al. (2013)	[335]	Friedrichstadt and Altstadt, Dresden (Germany)	RANS / YMEE	AT, SR	Urban planning, thermal comfort, pedestrian, district comparison, case comparison	AT, SR, UTCI
29	Srivani and Hokao (2013)	[336]	Honjo Campus of Saga University, Saga (Japan)	RANS / YMEE	AT, RH, SR, WV	Vegetation, pedestrian, case comparison, building form (roof), diurnal variation	AT, RH, SR, WV
30	Su et al. (2014)	[337]	HoHai University Campus, Nanjing (China)	RANS / YMEE	AT	Vegetation, coupling, sustainable, urban form, district comparison	AT
31	Hedquist and Brazel (2014)	[338]	Central Phoenix, Phoenix (USA)	RANS / YMEE	AT	Thermal comfort, seasonal variation, district comparison, pedestrian, materials	AT, PMV, ST
32	Middel et al. (2014)	[339]	North Desert Village, Phoenix (USA)	RANS / YMEE	AT, ST	Urban form, urban design, vegetation, case comparison, radiation (shading)	AT, ST
33	Maggiotto et al. (2014)	[340]	Several locations in Lecce (Italy)	RANS / YMEE	AT	Coupling, diurnal variation, model development, statistical analysis, heat transfer	AT, RH, SPI
34	Zoras et al. (2014)	[341]	Central Florina, Florina (Greece)	Not specified	AT, ST, WV	Bioclimatic design, materials, thermal comfort, case comparison, radiation (reflections)	AT, ST, WV
35	Park et al. (2014)	[342]	Nanaimo, British Columbia (Canada); Changwon (South Korea)	RANS / YMEE	SR	Pedestrian, thermal comfort, district comparison, coupling, urban form	AT, MRT, RH, SR, ST, UTCI, WV
36	Tang et al. (2014)	[343]	Shang-gan-tang village (China)	RANS / STKE	AT	Bioclimatic design, urban planning, vegetation, sustainable, water body	AT, WV
37	Minella et al. (2014)	[344]	Railway Station, Geneva (Switzerland)	RANS / YMEE	AT, MRT, RH, SR, WV	Thermal comfort, vegetation, case comparison, urban design, urban form	AT, MRT, RH, SPI, SR, UTCI, WV
38	Skellhorn et al. (2014)	[345]	Several locations in Manchester (England)	RANS / YMEE	AT, ST	Vegetation, adaptation, climate (change), building form (height), district comparison	AT, ST
39	Du et al. (2014)	[346]	Shuangjiang Town, Chongqing (China)	RANS / STKE	AT, WV	Building form, thermal comfort, diurnal variation, wind, energy (building)	AT, BEC, WV
40	Dimoudi et al. (2014)	[347]	Center of Serres (Greece)	RANS / STKE	AT, ST, WV	Materials, bioclimatic design, mitigation, case comparison, radiation (reflections)	AT, ST, WV
41	Acero and Herranz-Pascual (2015)	[348]	Several locations in Bilbao (Spain)	RANS / YMEE	AT, MRT, WV	Thermal comfort, district comparison, diurnal variation, statistical analysis, urban form	AT, MRT, PET, WV
42	Wang et al. (2015)	[349]	Assen (Netherlands)	RANS / YMEE	AT	Radiation (shading), vegetation, diurnal variation, seasonal variation, thermal comfort	AT, PMV, SPI
43	Tominaga et al. (2015)	[148]	Central Hadano (Japan)	RANS / RNGKE	AT, RH	Water body, case comparison, model development, wind, diurnal variation	AT, RH, ST, WV
44	Tan et al. (2015)	[350]	Tsim Sha Tsui and Sham Shui Po, Hong Kong (China)	RANS / YMEE	MRT, ST	Vegetation, mitigation, urban density, urban form, radiation (SVF)	AT, HF, MRT, ST, SVF, WV
45	Salata et al. (2015)	[351]	Sapienza University, Rome (Italy)	RANS / YMEE	AT, MRT, RH, SR	Thermal comfort, case comparison specific forms (courtyards), material, mitigation	AT, MRT, RH, SR, WV
46	Emmanuel and Loconsole (2015)	[352]	Several locations in Glasgow (Scotland)	RANS / YMEE	AT	Coupling, vegetation, different districts, adaptation, climate (future scenarios)	AT, ST
47	Grack et al. (2015)	[353]	Penn State Campus, University Park (USA)	RANS / RNGKE, RKE	AT	Urban density, diurnal variation, coupling, energy (building), wind	AT, BEC, ST
48	Toparlar et al. (2015)	[146]	Bergpolder Zuid, Rotterdam (Netherlands)	RANS / RKE	ST	Building form, adaptation, thermal comfort, model development, urban form	AT, ST, WV
49	Janicke et al. (2015)	[354]	Berlin Institute of Technology, Berlin (Germany)	RANS / YMEE	AT, MRT, RH	Vegetation, thermal comfort, case comparison, adaptation, building form (façade)	AT, MRT, RH
50	Song and Park (2015)	[355]	Several locations in Changwon City (South Korea)	RANS / YMEE	AT	Vegetation, materials, district comparison, statistical analysis, radiation (reflections)	AT, SPI, ST
51	Liu et al. (2015)	[356]	Penn State Campus, University Park (USA)	RANS / MDKE	AT	Building form, energy (building), CHTC, coupling, urban density	AT, BEC, CHTC, ST
52	Elhabawi et al. (2015)	[357]	Cairo (Egypt)	RANS / YMEE	AT, MRT, RH	Thermal comfort, climate, urban form, pedestrian, radiation	AT, MRT, RH, SR
53	Wang and Zacharis (2015)	[358]	Beijing (China)	RANS / YMEE	AT	Vegetation, mitigation, sustainability, thermal comfort, urban design	AT, ECN, MRT

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Table 4 (continued)

#	Authors (year)	Ref.	Location (Country)	Equations / Models	Validation parameter	Keywords	Parameters
54	Yang et al. (2015)	[359]	Singapore (Singapore)	RANS / YMEE	AT, MRT, RH, WV	Aspect ratio, thermal comfort, urban form, case comparison, radiation	AT, MRT, PET, RH, WV
55	Peron et al. (2015)	[360]	Venice (Italy)	RANS / YMEE	AT	Mitigation, case comparison, materials (albedo), vegetation, building form	AT
56	Zoras (2015)	[361]	Arta (Greece)	RANS / SSTKW	AT, ST, WV	Climate sensitive design, adaptation, thermal comfort, specific forms (open space), case comparison	AT, ST, TSP, WV
57	Duarte et al. (2015)	[362]	Sao Paulo (Brazil)	RANS / YMEE	AT, SR	Vegetation, urban form, urban density, thermal comfort, climate	AT, PET, SR, ST, TEP

Abbreviations: AKN k- ϵ [149] (AKNNE); Chen-Kim Extended k- ϵ (CKEKE) [150]; Deardorff Subgrid-scale [159] (DSGS); Durbin k- ϵ [151] (DKE); Eddy Diffusivity [101] (ED); Low Reynolds Number k- ϵ [149,152] (LRNKE); Miao E- ϵ [153] (MEE); Modified k- ϵ [131] (MDKE); Realizable k- ϵ [154] (RKE); RNG k- ϵ [155] (RNGKE); Smagorinsky-Lilly Subgrid-scale [160] (SSTKW); Standard k- ϵ [157] (STKE); Yamada and Mellor E- ϵ [158] (YMEE). Air change rate (1/hour) (ACH); Air quality index (-) (AQI); Air temperature ($^{\circ}\text{C}$) (AT); Building energy consumption (W) (BEC); Convective heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$) (CHTC); Dry-bulb temperature ($^{\circ}\text{C}$) (DBT); Economy (currency) (ECN); Froude number (-) (Fn); Heat flux (W/m^2) (HF); Indoor air temperature ($^{\circ}\text{C}$) (IAT); Mean radiant temperature ($^{\circ}\text{C}$) (MRT); Physiological equivalent temperature ($^{\circ}\text{C}$) (PET); Predicted mean vote (-) [162] (PMV); Extended PMV (-) (EPMV) [163]; Pressure (coefficient) (CP); Pollutant concentration (%) (PC); Pressure distribution (PD); Relative humidity (%) (RH); Richardson number (-) (Ri); Sky view factor (-) (SVF); Solar access index (-) (SAD); Solar radiation (W/m^2) (SR); Standard effective temperature ($^{\circ}\text{C}$) [164] (SET); Statistical Performance Indicators (various, e.g. Correlation coefficient) (SPD); Surface temperature ($^{\circ}\text{C}$) (ST); Temperature-humidity index (-) (THI); Temperature of equivalent perception ($^{\circ}\text{C}$) [165] (TEP); Thermal Sensation Perception [166] (TSP); Turbulence dissipation rate (m^2/s^3) (TDR); Turbulent kinetic energy (m^2/s^2) (TKE); Universal thermal climate index ($^{\circ}\text{C}$) [167] (UTCI); Ventilation rate (l/minute) (VR); Water vapor fraction (%) (WV); Wet black globe temperature ($^{\circ}\text{C}$) (WBGT); Wind comfort index (-) (WCI); Wind velocity (m/s) (WV); Wind velocity vectors (WVV).

3.2. CFD equations/models

Among the investigated 183 studies, 7 of them did not specify the approximate form of the governing equations used. As for the remaining 176 studies, 169 (96.0%) used only RANS, 5 used only LES (2.8%) and 2 used both LES and RANS (1.1%) as approximate form of the governing Navier-Stokes equations.

A microclimatic CFD simulation that couples the temperature and velocity fields has a higher computational cost and the choice of LES over RANS evidently will increase this cost. It is expected that the increased computational cost and the often sufficient accuracy of RANS [146,304,363,364] are the two main reasons why the vast majority of studies was performed with RANS, even though LES is generally considered to be more accurate than RANS [19,29,73,86,89,292,300,304,363–368]. Apart from RANS and LES, the third approach often used in CFD simulations, that is Direct Numerical Simulation (DNS) is not utilized among the microclimate studies investigated here. Due to its dominant use in the investigated studies, the remainder of this section will focus on the RANS approach.

Fig. 10 shows the distribution of the use of turbulence models in these studies. Among the 171 studies using RANS, 6 of them [201,210,220,291,324,353] have considered two or more turbulence models.

The most commonly used turbulence model is the Yamada and Mellor E- ϵ [158] turbulence model (used in 86 studies, or 49% of total). Although this turbulence model is not explicitly recommended or adopted in the CFD best-practice guidelines [19,75–78], its popularity results from it being the only available turbulence model option in the microclimate simulation tool ENVI-Met [168]. The second most popular turbulence model is the standard k- ϵ [157] model (used in 45 studies – 25%). The RNG k- ϵ [155], Realizable k- ϵ [154] and Modified k- ϵ [131] turbulence models appear to have similar popularity compared with each other. The standard k- ϵ model [157] is one of the most popular turbulence models among CFD studies [76] but as argued in several publications [75,95,364], some improved models, such as the realizable k- ϵ model [154] can show better performance in resolving the mean flow field. Fig. 11 illustrates the use of turbulence models over the years 2010–2015 and the popularity of YMEE (the turbulence model used in ENVI-met) as mentioned before. The figure also shows that except for the year 2014, more recent CFD studies are now using turbulence models other than standard k- ϵ more often.

3.3. Target parameters

As shown in the foregoing tables, the majority of the studies considered more than one target parameter. Fig. 12a shows the distribution of the target parameter categories used and Fig. 12b shows the distribution of the seven most used target parameters. Most studies considered temperature related parameters, especially air temperature for comparison, evaluation or validation purposes. This parameter is followed by wind velocity, surface temperature and mean radiant temperature.

Target parameters related to fundamental fluid flow or heat transfer, such as TKE and CHTC, are mostly used in studies with generic urban areas. Among the eight studies that considered CHTC as a target parameter, seven were conducted in generic urban domains and for the TKE, this ratio is found to be 4/5. This is further evidence that studies on real urban areas do not typically consider parameters related to fundamental flow aspects, which can be explained by their larger complexity or by their difficulty for collecting measurement data. Economic parameters and statistical performance indicators can be used in communicating the results from urban microclimate studies to professionals from other disciplines, such as policy makers, as these aspects may lead to more generalized conclusions. However, although these target parameters are considered in some recent CFD urban microclimate studies, their use is still limited, with only 2 of 183

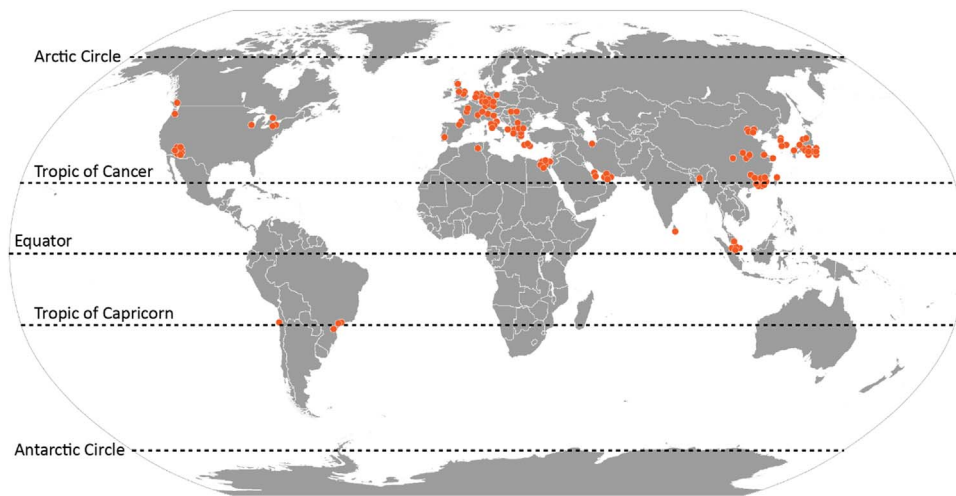
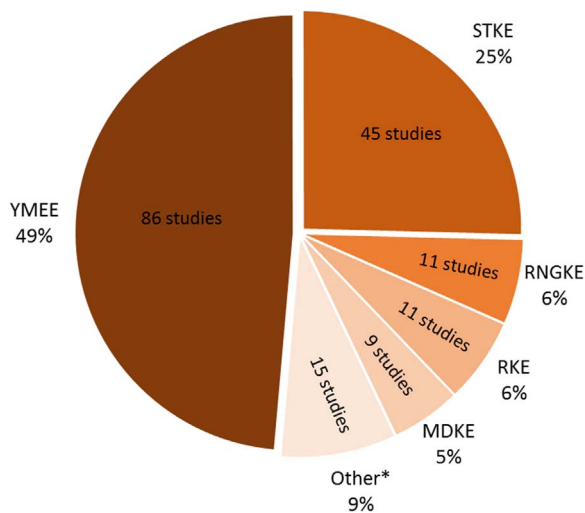


Fig. 9. Distribution of the locations of the CFD microclimate studies focusing on real urban areas. Every orange dot represents one study.



*Studies with SSTKW, MEE, ED, DKE, LRNKE, AKNKE, CKEKE

Fig. 10. Distribution of the turbulence models in studies with RANS simulations. Abbreviations: AKN k- ϵ [369] (AKNKE); Chen-Kim Extended k- ϵ (CKEKE) [150]; Durbin k- ϵ [151] (DKE); Eddy Diffusivity [101] (ED); Low Reynold Number k- ϵ [149,152] (LRNKE); Miao E- ϵ [153] (MEE); Modified k- ϵ [131] (MDKE); Realizable k- ϵ [154] (RKE); RNG k- ϵ [155] (RNGKE); SST k- ω [156] (SSTKW); Standard k- ϵ [157] (STKE); Yamada and Mellor E- ϵ [158] (YMEE).

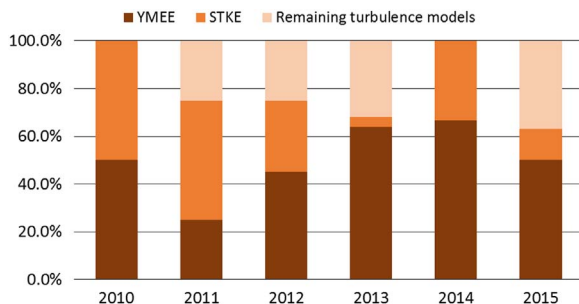


Fig. 11. Percentage distribution of the turbulence models used in the last 6 years for closure in RANS studies. 'Remaining turbulence models' include AKNKE, CKEKE, DKE, ED, LRNKE, MDKE, MEE, RKE, RNGKE and SSTKW.

studies using economical parameters and 4 of 183 using statistical performance indicators.

As CFD has demonstrated its capability for involving multiple scales, there is an increasing interest in linking the results from microclimate analysis with building scale aspects, such as building

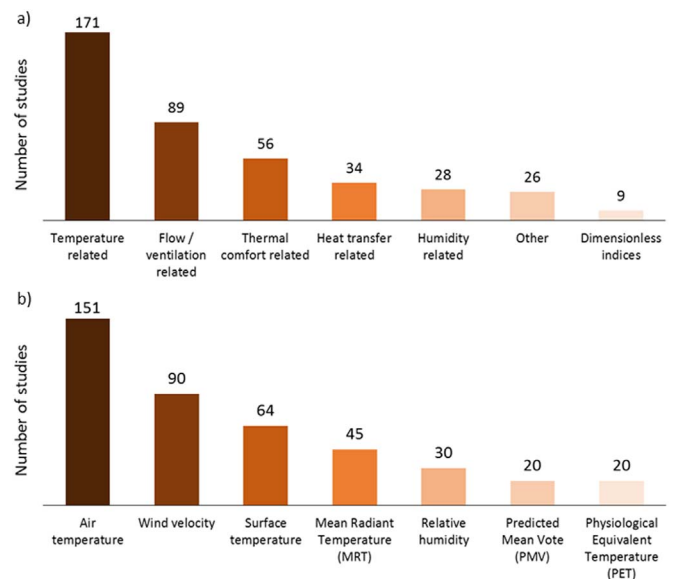


Fig. 12. Distribution of the studies based on the target parameters considered. a) Target parameter categories; b) Seven most used target parameters.

energy consumption and indoor air temperature. Even though these parameters are not yet considered quite often (BEC 16 of 183 studies and IAT 1 of 183 studies), while the oldest study specifying one of these parameters is only from the year 2011 [182], 11 of these studies are from the last two years, demonstrating the increasing interest.

3.4. Keywords

As described in Section 2, keywords are selected either directly from the provided keywords list or from the titles and abstracts of investigated papers. Keywords with similar or interchangeable use were grouped in 37 keyword categories and five keywords per study were identified, as listed in Tables 1–4. According to this procedure, the most used three keywords in CFD urban microclimate studies are: vegetation (90 studies), case comparison (78 studies) and thermal comfort/heat stress (77 studies).

Apart from the number of studies, in this paper, we suggest and apply additional metrics for documenting the annual use of the keywords. One of them is the first year a keyword is introduced in CFD urban microclimate studies (First Year Index = FYI). A second metric called "Weighted Year Index" (WYI) is defined as the weighted average year of a particular keyword's usage:

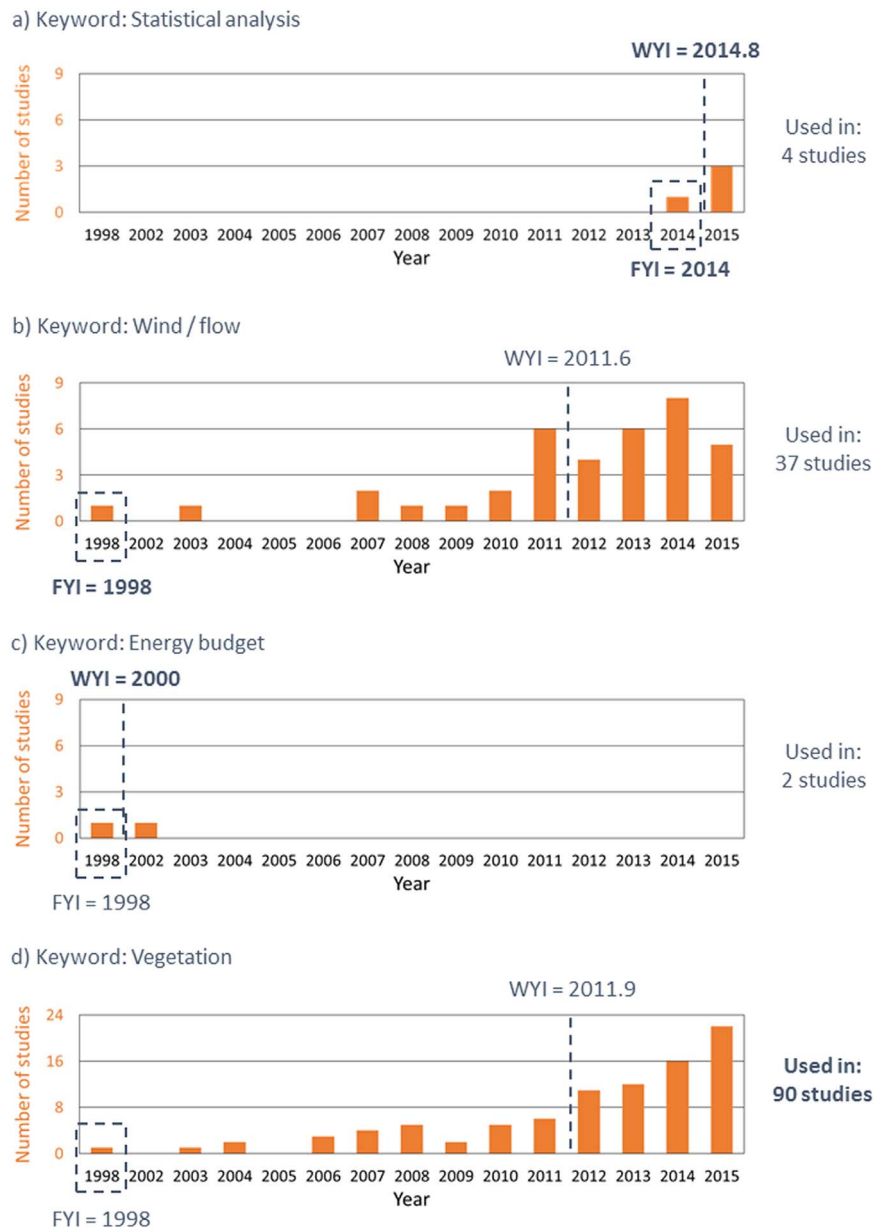


Fig. 13. The annual use of four of the a) Statistical analysis (keyword with the highest WYI and FYI), b) wind / flow (keyword with the lowest FYI), c) Energy budget (keyword with the lowest WYI) and d) vegetation (the most common keyword).

$$WYI = \frac{\sum_{y_0}^{y_n} y * k_y}{\sum_{y_0}^{y_n} k_y} \quad (1)$$

with y the year, y_0 the year of the earliest study, y_n the year of the latest study (as investigated in this paper), and k_y is the number of times a keyword is used in the y^{th} year. This metric indicates the year associated with a keyword's average use. A lower WYI means that the use of a particular keyword is mainly situated in earlier years, while a higher WYI means that the keyword use is mainly situated in recent years.

According to the analysis, of all 37 keywords, the keyword with the highest FYI and WYI is “statistical analysis” (FYI = 2014, WYI = 2014.8), while that with the lowest FYI is “wind / flow” (FYI = 1998)⁸ and that with the lowest WYI is “energy budget” (WYI = 2000). The

⁸ As every study has five keywords, and the earliest study is from the year 1998, the keyword wind / flow shares the lowest FYI = 1998 along with other keywords from the same study [168], namely model development, vegetation, heat transfer and urban form / morphology.

annual use of these keywords along with that of the most common keyword (vegetation) is illustrated in Fig. 13.

A more comprehensive view of the relationship between the historical use of keywords and the associated number of studies, or between the FYI and the WYI and number of studies, is given in Fig. 14. This chart graphically demonstrates the number of times each keyword is used (by size of the circle), whether a keyword is relatively new or old (indicated by FYI on horizontal axis) and whether a keyword is used more often in earlier or more recent years (indicated by the WYI on the vertical axis). The average overall metrics for the ensemble of all keywords are: average number a keyword is used: 24.7, average FYI: 2004.3 and average WYI: 2011.9. The latter two numbers define the origin of the coordinate system in Fig. 14.

Fig. 14 shows that the keyword use in CFD studies of urban microclimate has transitioned from keywords related to model development (heat energy budget, turbulent heat fluxes, model development) to keywords related to urban scale adaptation measures (e.g. adaptation, climate sensitive design) and energy (e.g. building energy, sustainable). Highly used keywords with large circles in Fig. 14, such as

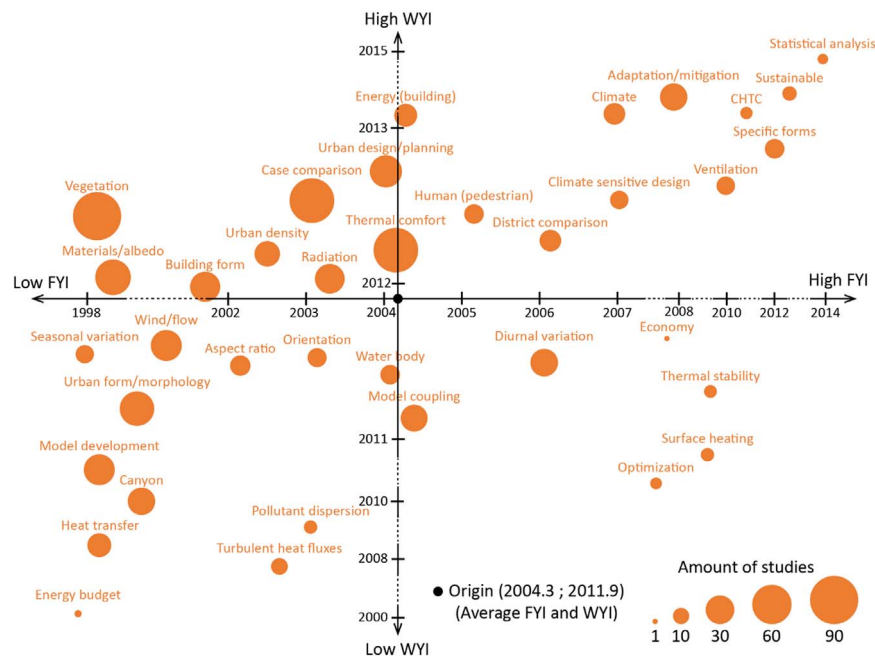


Fig. 14. Chart of historical keyword analysis. The X-axis location of a keyword is determined by the first year a keyword is used (FYI); the Y-axis location is determined by the weighted year index (WYI), and the amount of studies with each keyword is indicated by the size of the respective orange circle.

vegetation, case comparison, thermal comfort, materials/albedo and urban design/planning are keywords which are used since the early years of this research field and are still very commonly employed.

4. Discussion and future perspectives

4.1. Validation studies

According to the American Institute of Aeronautics and Astronautics (AIAA), validation is “the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model” [370]. According to several CFD best practice guidelines [19,75–78,292], CFD simulations should be evaluated critically and the results should only be considered reliable after comparing with some measurement data. If measurement data are hard to obtain for a specific case, sub-configuration validation can be performed for the intended use of the model [19]. One example of a sub-configuration validation is the study by Gromke et al. [275] where the authors used a vegetation model which is validated with measurement data in separate CFD simulations and then used the same model in a real urban area. The advantage of sub-configuration validation can be relevant for complex studies with different physical models, as the classical validation of the whole simulation setup can be difficult to conduct due to the uncertainty in parameters.

According to this review, the majority of the CFD urban microclimate studies (105 of 183 studies) are conducted without validation. The percentage share of the studies without validation seems to have remained rather stable in the last years, as demonstrated in Fig. 15. However, it is imperative that CFD urban microclimate studies include validation much more often to ensure the desired reliability and predictive capability.

The most common reason for the absence of validation in CFD microclimate studies might be the lack of relevant and well-documented measurement data. Measurement campaigns on urban areas can have some challenges such as logistic difficulties, data quality issues (e.g. ventilated vs non-ventilated temperature measurements) and problems with spatial representativeness.

Although these challenges remain, difficulties in obtaining relevant data can be overcome in a much better-connected World. Internet resources can be a good alternative for measurement data as large datasets are now within reach. For instance, surface temperature data for various locations around the world can now be obtained from the National Oceanic and Atmospheric Administration’s (NOAA) satellite imagery dataset. In one of the plenary session presentations during the 9th International Conference on Urban Climate (ICUC9), Chapman [371] mentioned the possibility of using low-cost air temperature sensors with WiFi network, distributed vastly in urban areas. Such a network could have the potential of becoming a part of *Internet of Things* [372,373] and consequently could provide a large amount of measurement data for microclimate researchers. In the future, researchers can investigate such resources carefully to find relevant measurement datasets to validate their CFD simulation results.

4.2. Urban locations

Fig. 9 illustrated the limited variety of studied urban locations. In the article entitled *Urban Climatology: History, status and prospects*, Mills [17] identifies one of the major challenges in the urban climatology field as: “acquiring information on the climates of cities in less prosperous regions, which are growing rapidly and many of which have tropical climates in which there have been few studies”. Although this statement was made referring to urban climatology

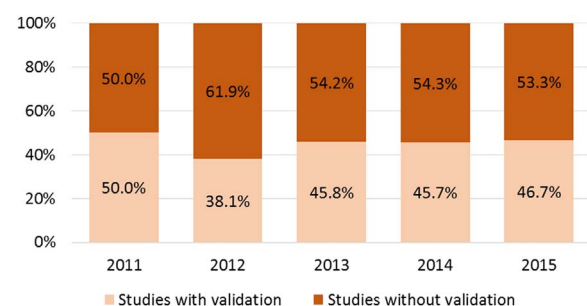


Fig. 15. Distribution of the studies with and without validation for the last five years.

studies in general, CFD urban microclimate studies are following a similar route. According to the UN World Urbanization Prospects [2], most of the urbanization expected to occur in the 21st Century will take place in the developing regions of the World. Therefore, in the future, more studies are needed focusing on urban areas in these regions, especially on the ones with high/increasing populations (e.g. African continent, India, Latin America).

Another observation in the location analysis is the relation between the study location and the physical location of the respective research groups. Mostly, research groups with expertise in CFD urban microclimate studies investigate the city in which they are located or to which they are closely situated. In the future, researchers should aim at expanding the CFD knowledge to various parts of the World and should not limit themselves to their own vicinity.

Most of the reviewed papers focus on the negative consequences of the UHI effect (e.g. on heat stress, energy demand). Therefore, adaptation/mitigation measures aiming mostly at temperature reductions are proposed and scientifically tested for implementation in the various parts of the World. However, the UHI effect may not necessarily always cause negative consequences. The numerical study by Hirano and Fujita [11], focusing on the climate and building stock of Tokyo has shown that for residential buildings, the UHI effect can have a net positive effect on the building energy demand on a yearly basis. It is safe to assume that if a city is located in colder climate zones, the UHI might actually be beneficial. Future CFD studies can investigate in more detail the consequences of the UHI effect in the colder parts of the World.

Furthermore, the reviewed studies are mostly conducted for cities in the mid-latitudes and cities near the arctic circles are not considered often. Among the reviewed studies, the urban area closest to the Arctic or Antarctic Circle, was Glasgow [352]. Some higher latitude cities, such as Oslo, Stockholm or Moscow can be considered in future CFD urban microclimate studies and new information can be gained. Note that the lack of urban planning and urban microclimate studies in the arctic regions is mentioned in a recent study by Ebrahimabadi et al. [374]. Similarly, (sub)tropical regions are not often considered in CFD microclimate studies. According to Roth [375], among all the urban climate studies, studies on sub(tropical) regions constitute less than 20% and according to the present review, this ratio is 8% (15 of 183 studies).

4.3. CFD equations/models

Almost half of the investigated studies used the ENVI-Met [168] software. This software combines several physical phenomena (e.g. fluid flow, heat transfer, mass transfer, vegetation interactions) for urban microclimate analysis. Limited modeling options in the software, such as the availability of only one turbulence model (Yamada and Mellor E- ϵ [158]), the limited options for grid generation and the lack of information about wall functions, can be considered as drawbacks. Such limitations and their possible implications on the results are mentioned in several studies which were included in this review paper [175,312,319,333,339,349].

After the Yamada and Mellor E- ϵ [158], the second most commonly used turbulence model is the standard k- ϵ turbulence model [157]. Over the years, the standard k- ϵ turbulence model has been used in many CFD studies but it is well-known that with this turbulence model, the production of kinetic energy near the frontal corners of buildings is overestimated and that the turbulent kinetic energy in wake regions is underestimated (e.g. [76,376]). Various CFD best practice guidelines [19,76,77] referred to this problem and advised the use of other turbulence models, such as realizable k- ϵ [154]. Among the reviewed studies, the standard k- ϵ turbulence model [157] is used many times (45 of 183 studies) but

turbulence models such as realizable k- ϵ [154] (used in 11 of 183 studies) or RNG k- ϵ [155] (used in 11 of 183 studies) are gaining popularity. Among the 22 studies using one of these two turbulence models (realizable and RNG k- ϵ), 17 are published in the last three years.

In many CFD review papers and best practice guidelines on urban flow fields, LES is reported as superior to RANS simulations in terms of results accuracy compared with measurements [19,29,73,86,89,292,300,304,363–368]. According to this review, the LES approach is not yet very popular for urban microclimate studies, as only less than 5% of studies followed this approach. Computational requirements and the lack of best practice guidelines for the use of LES can be the two main reasons for this. However, in the near future, rapid developments in the computational resources can and should result in more studies with LES approach.

4.4. Target parameters

Most of the CFD urban microclimate studies focused on parameters related to temperature, wind flow, thermal comfort and heat transfer. CFD has repeatedly demonstrated its predictive capability in validation studies focusing on different parameters. The three most commonly used parameters are air temperature (151 of 183 studies, 82.5%), wind velocity (90 of 183 studies, 49.2%) and surface temperature (64 of 183 studies, 35.0%).

Measurement data for air temperatures is relatively easier to obtain compared with surface temperatures and thus are used more often. The accurate prediction of surface temperatures can be harder as surface heat transfer modeling requires appropriate near-wall modeling. Therefore, validation of surface temperatures can be a more vigorous test for the predictive capability of CFD simulations.

Some past studies used the percentage difference in predicted and measured temperatures for evaluating the simulation performance. Such comparisons can be improved in the future, as the outcome of percentage difference in temperatures would be different for every temperature unit. For validation studies, dimensionless parameters and/or statistical performance measures can be used more frequently to evaluate the performance of simulation approaches.

CFD and complementary numerical tools can be used to link climate studies from different scales. For instance, the results from urban microclimate simulations can be employed as boundary conditions for simulations at building or indoor scale. This is necessary to accurately assess the effect of urban microclimate on building energy demand and/or indoor ventilation. This review showed that target parameters such as building energy consumption and ventilation rate are not very common; though parameters related to building energy consumption have an increasing popularity. Future studies can focus on these parameters, which can create a deterministic link between urban design and building design [377].

The relevance of urban climatology for urban designers and policy makers is mentioned in several review studies [17,378–380]. Policy makers and/or professionals responsible for public resources (e.g. local municipalities) are interested in the economic consequences of planned adaptations or modifications in urban areas [381]. In the past, microclimate studies (not with CFD approach) have showed the positive economic consequences of adaptation measures on key issues such as energy demand, thermal comfort and human productivity. CFD simulations can be coupled with financial models to obtain deterministic results on the economic aspects of adaptation measures. So far, the reviewed studies showed that the economic aspects are almost never considered with a relevant target parameter. The missing link between fundamental microclimate studies and the economic consequences can be an important aspect in the near future.

4.5. Keywords

The keywords can be classified in four categories based on the quadrants in Fig. 14.

Keywords with low FYI and low WYI, such as heat transfer, model development, energy budget and turbulent heat fluxes were mainly used in the earlier studies and are not used very often in the later studies. With more validated CFD approaches, research efforts have shifted from the development of new models to case studies.

Keywords with low FYI and high WYI, such as materials/albedo and vegetation are used in CFD urban microclimate studies since the early 2000s and they are still used very often. Vegetation is the most common keyword as many studies investigated the effect of street trees, urban parks and green roofs/facades since the early years of this research field and still, similar studies are conducted for different cities.

Keywords with high FYI and high WYI are not used very often yet, because they are very recent. Among the new keywords with high WYI values, adaptation/mitigation and climate sensitive design are gaining popularity not only among the CFD studies but also among studies with different methodologies [20,382]. New keywords such as “sustainable” and “climate” demonstrate the effect of the popularized sustainable development challenge on this research field.

Keywords with high FYI but with low WYI values, such as model coupling, thermal stability and optimization refer to studies, which are recent but are not very common. Typically, studies with these keywords are very specialized. For instance, the “optimization” keyword belongs to this group and the parametric optimization of CFD results would require many simulations, with a dedicated campaign, which may have affected its FYI and WYI values.

In the future, many of the new keywords are expected to continue to increase their popularity. Among these new keywords, statistical analysis should play an important role in testing new models and simulation cases more effectively. The economic aspects of adaptation/mitigation strategies should be evaluated with new methods, possibly by linking multiple scales. Even though the effects of vegetation and materials on urban microclimate seem to be well understood, it might continue being investigated with new case studies and with studies performed on generic urban areas to provide general conclusions (or guidelines) for professionals from other disciplines. CFD is a useful tool for deterministic judgement and researchers in these other disciplines should benefit from this.

4.6. Limitations of the review

Given the large scope and large number of publications in this topic, some studies had to be omitted from this review. As denoted in Section 2, this review identified CFD microscale studies, which couple velocity field with temperature field on 3D computational domains. CFD studies on urban microscale investigating pedestrian wind comfort [82,383,384] and thermal comfort [385], are not investigated in this review if their focus was only on the modeling of velocity field, without the coupling with temperature. In addition, this review paper focused only on journal papers which are prepared in English language but surely, valuable studies on CFD urban microclimate analysis have been published in the past as conference papers (e.g. [386–388]) or in other languages (e.g. [389,390]).

5. Conclusions

Considering the trend towards urbanization and the challenge of sustainable habitats, studies on urban microclimate will continue to gain popularity in the 21st century. Numerical methods to analyze urban microclimate are essential tools for engineers, architects, urban planners and policy makers to compare urban design alternatives and to manifest guidelines. CFD is one of these numerical tools, which is frequently used

in the urban climate at various spatial scales. CFD studies on the meteorological microscale, where typical spatial distances are less than 2 km, are gaining popularity due to their advantages such as the explicit modeling of urban and building geometry and resolving the flow field with high spatial resolution. Though gaining popularity, to the best of our knowledge, there has been no review paper yet that is dedicated to CFD studies on urban microclimate.

This paper presented a systematic review and analysis of the CFD urban microclimate studies that were published in peer-reviewed international journals from 1998 until the end of 2015. A total of 183 studies were identified which include 3D computational domains and couple the velocity and temperature fields. The studies were categorized based on the types of urban areas investigated, real or generic, and on the methodology followed, studies with and without validation.

For every sub-category, the studies were listed in tabular form based on their publication year, location, CFD equations/models, validation parameter (if any), keywords and target parameters. A comparative analysis was provided based on the findings.

From this review paper, the following conclusions can be made:

- CFD results should be subjected to detailed validation in the future. This review documented that 58% of the existing CFD microclimate studies have not considered any validation. In order to improve the reliability and the predictive capability of CFD simulations, future studies should collect and employ relevant measurement data to support simulation results.
- Even though CFD urban microclimate studies are gaining popularity, the urban locations investigated do not have a large variety. Among the 122 studies focusing on real urban areas, only 74 cities from 30 countries have been the subject of CFD simulations. Especially for the cities located in the developing regions and in the tropics, very few studies can be identified. CFD urban microclimate knowledge needs to be expanded to the developing regions of the World.
- The review documented that 96% of the studies considered RANS simulations only, even though LES has the potential to be more accurate in predicting flow field.
- Among the RANS simulations, 74% used either Yamada-Mellor E-ε or standard k-ε turbulence models. The choice of turbulence models can be limited with the availability of the software packages. However, detailed validation studies and the resulting increased accuracy and reliability of CFD studies will benefit from the availability and/or use of more turbulence models.
- The results from validation studies can be communicated using statistical performance indicators, which were not used in the past studies often. Moreover, the target parameters can be selected from other spatial scales (e.g. building energy demand) or from generic terms (e.g. economy, emissions) for a thorough analysis on the effect of microclimate and adaptation measures on humans, buildings and urban infrastructure.
- The themes of CFD urban microclimate studies were documented by investigating the keywords they used. According to this investigation, the early CFD urban microclimate studies had been conducted for model developments and case studies. In the past few years, more studies about urban scale adaptation measures and thermal comfort are conducted. Future studies might focus more on systematic studies with multiple scales (e.g. mesoscale, building scale) and aspects (e.g. economical) to transfer the gained knowledge from urban climatology to routine building and urban design guidelines.

These recommendations are in fact against the current trends observed among CFD urban microclimate studies. Future studies on this topic can consider these recommendations to push the boundaries of this field for acquiring new knowledge on urban climatology.

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